TR 202

TECHNICAL REPORT

SOME RESULTS OF AN OCEANOGRAPHIC SURVEY IN THE NORTHERN GREENLAND SEA, SUMMER 1964

MARCH 1968

NAVAL OCEANOGRAPHIC OFFICE
WASHINGTON, D.C. 20390
Price 90 cents

ABSTRACT

Oceanographic data were collected during a cruise of USS EDISTO (AGB 2) to the northern Greenland Sea and adjacent Arctic Ocean during the summer of 1964. The resulting data indicate that many of the prevailing ideas concerning the oceanography of the region are correct, but some modifications and additions are suggested.

The center of the East Greenland Current appeared to be farther east than is indicated on some earlier charts, and the meanders and gyres also differed from those shown in some earlier current schemes.

Minimum bottom water temperatures in the survey region appear to be warmer than they were at the beginning of the century, and some current ideas on the formation and movement of Arctic Bottom Water do not seem to be well substantiated.

High dissolved oxygen saturations were found at great depths and can be explained by the proximity of areas of bottom water formation, by the oxidation of a large portion of organic material before the deeper waters left the surface, and by the absence of a significant amount of sinking organic material.

Micronutrient concentrations were low indicating that water from the North Atlantic was the primary component of the waters in the survey region. Photosynthetic processes appeared to be lowering near-surface micronutrient concentrations and, in some instances, raising oxygen concentrations. In cases where production may have been limited by micronutrient deficiencies, nitrate appears to have been the limiting nutrient. No pronounced oxygen minimum or micronutrient maxima were encountered within a definite depth range in the survey area. Micronutrient relationships in the different water masses differed and can be explained to some extent by current theories on the formation and movement of these waters.

FOREWORD

A comprehensive survey was conducted by NAVOCEANO in the northern Greenland Sea during the summer of 1964. In this region, many important and interesting oceanographic features result from the interchange of Atlantic and Arctic waters. The data from this survey support many of the ideas of previous investigators and suggest some refinements. The micronutrient samples collected on this survey add substantially to the existing data from this area.

L. E. DeCAMP
Captain, U.S. Navy
Commander

CONTENTS

Page

FIGURES

TABLES

Page

APPENDIX

I. INTRODUCTION

During the summer of 1964, an oceanographic survey was conducted in the northern Greenland Sea and adjacent Arctic Ocean aboard USS EDISTO (AGB 2). Fifty stations were occupied between 31 August and 14 September (Fig. 1). The purpose of this report is to present and to interpret some of the physical and chemical data collected at these stations. Four additional oceanographic stations for ice forecasting were occupied to the south of the main survey area but are not discussed in this report.

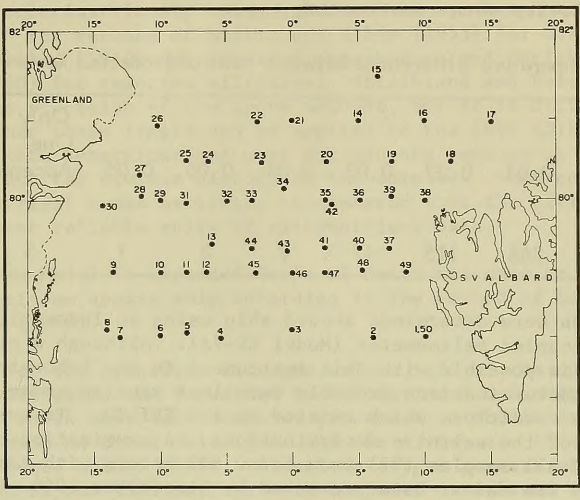

Figure 1. Oceanographic Station Locations

The following scientists participated in the survey.

NAME	OCCUPATION	ACTIVITY
Keith R. Newsom	Oceanographer	NAVOCEANO
Jess Coleman	Oceanographer	NAVOCEANO
Richard Wargelin	Oceanographer	NAVOCEANO
Donald Chandler	Bathymetrist	NAVOCEANO
Lt. K. Palfrey U.S.C.G.	Graduate Student	University of Washington

II. METHODS AND INSTRUMENTS

Navigation in the survey area is poor, and it is possible that some station locations are in error by as much as 20 miles. The appendix lists the primary method of navigation used to determine the position of each station and the navigator's estimate of the relative accuracy of the position.

Water samples were collected with tin-lined Nansen bottles. Each bottle was equipped with two protected reversing thermometers, and some were equipped with an additional unprotected reversing thermometer in order to obtain thermometric depths. Precision of the protected thermometers was good (Table I), and it appears that errors of more than $\pm 0.02°C$ were rare. Occasionally, the paired thermometers were rearranged to reduce the possibility of recurring systematic errors. Thermometric depths were computed by the L-Z curve method described in H.O. Pub. 607. Often, agreement between unprotected thermometers in a cast was not good, and it was necessary to consider the thermometers' previous histories when constructing the curves.

TABLE I. Temperature Differences Between Pairs of Protected Reversing Thermometers

Temp. Diff. °C	0.00	0.01	0.02	0.03	0.04	0.05	0.06	Only One Accepted	None Accepted
No. Obs.	225	268	115	47	7	3	1	5	6

Salinities were determined aboard ship using an Industrial Instruments inductively coupled salinometer (Model RS-7A). Although a precision of ± 0.003‰ is possible with this instrument in the laboratory, the salinity determinations probably were less precise under the more rigorous conditions which existed on the EDISTO. To assess the accuracy of the salinity determinations, an examination of the salinities of all samples (97) from below 500 meters with temperatures less than 0°C was made. Data presented by Gladfelter 1964, Helland-Hansen and Nansen 1909 and 1912, Mosby 1959, Nansen 1915, and Sverdrup 1933 indicate that these samples should have a narrow salinity range with a mean salinity of approximately 34.91 to 34.92‰. Excluding questionable values, the average salinity of the 97 EDISTO samples is 34.91‰. If it is assumed that the 'true' salinity variation in these samples is ± 0.01‰, then 90% of the observations fell within ± 0.02‰ of the 'true' range, 94% fell within ± 0.03‰, and, except for one value, all of the salinities fell within ± 0.04‰ of the 'true' range. Values which were considered questionable were included in this comparison.

Dissolved oxygen and nitrogen concentrations were determined by the gas chromatographic method described by Swinnerton and Sullivan (1962). It was assumed that the dissolved nitrogen concentrations of the sea water samples should approximate the 100% saturation values given by Rakestraw and Emmel (1938), and when the deviations from saturation were greater than $\pm 10\%$, the results were not accepted. Ninety-nine comparison samples were analyzed for dissolved oxygen by the Naval Oceanographic Office's (NAVOCEANO) modification of the Winkler titration. However, comparisons were made only when the

dissolved nitrogen values obtained from the gas chromatograph were within the acceptable range. Eighty-seven sample pairs were compared, and the mean difference was found to be 0.36 ml/liter or approximately 5% of the dissolved oxygen content of the samples ($\approx$6-9 ml/liter). Winkler oxygen results for stations 15, 25, and 30 were used for analysis in this report because they were considered more reliable than the gas chromatographic results.

Micronutrient samples were collected in polyethylene bottles, frozen, and shipped to NAVOCEANO for analysis. Concentrations were determined colorimetrically using a Beckman DU spectrophotometer according to the methods of Mullin and Riley (1955) for nitrates, Murphy and Riley (1962) for reactive phosphorus, and Strickland and Parsons (1960) for reactive silicates. Strickland and Parsons (1960) estimate the precision of the above methods, but it is difficult to say whether these limits can be applied to the 1964 EDISTO samples since duplicate determinations were not run and because it is impossible to reconstruct the storage history of the samples. When constructing the micronutrient cross sections, it appeared that the nitrate values were the least reliable suite of micronutrient data.

A Beckman Model 76 Expanded Scale pH Meter was used to perform pH determinations aboard ship according to the method of Strickland and Parsons (1960).

Except for the dissolved nitrogen values, all of the data mentioned above were evaluated and forwarded to the National Oceanographic Data Center where they were computer processed to obtain calculated properties such as sound velocities and where they are filed under cruise reference number 31688. Dissolved oxygen percent saturations and apparent oxygen utilizations were computer determined at NAVOCEANO. In performing these calculations it was assumed that the oxygen solubility data of Carpenter (1966) were the most correct. These data and the dissolved nitrogen data are filed at NAVOCEANO.

In addition to Nansen cast station data, 36 bottom sediment samples were taken: 3 Kullenberg gravity cores, 32 Phleger cores, and 1 grab sample. These samples were forwarded to NAVOCEANO for analysis and are on file in the geological laboratory under item number 275.

Bathymetric data were obtained with an Alden 418 Precision Graphic Recorder and are on file at NAVOCEANO.

III. DESCRIPTION OF THE SURVEY REGION

1. Bathymetry.

Bathymetry of the northern Greenland Sea is complex. Bordering shelves of Greenland and Svalbard are deeper than average, and available data indicate that their topography is quite irregular. Glacial troughs appear to be common on both shelves. Canyons do not commonly

appear on the slopes bordering these shelves, but this may be merely a reflection of the paucity of soundings from these regions.

Figure 2, which has been adapted from a chart presented by Johnson and Eckhoff (1966), depicts the bathymetry of the northern Greenland Sea. This chart does not extend into the northernmost portion of the survey region, but available charts of that region are based on such a small amount of data that a mental extrapolation of Johnson and Eckhoff's chart will probably give the reader the best idea of the bathymetry of that area.

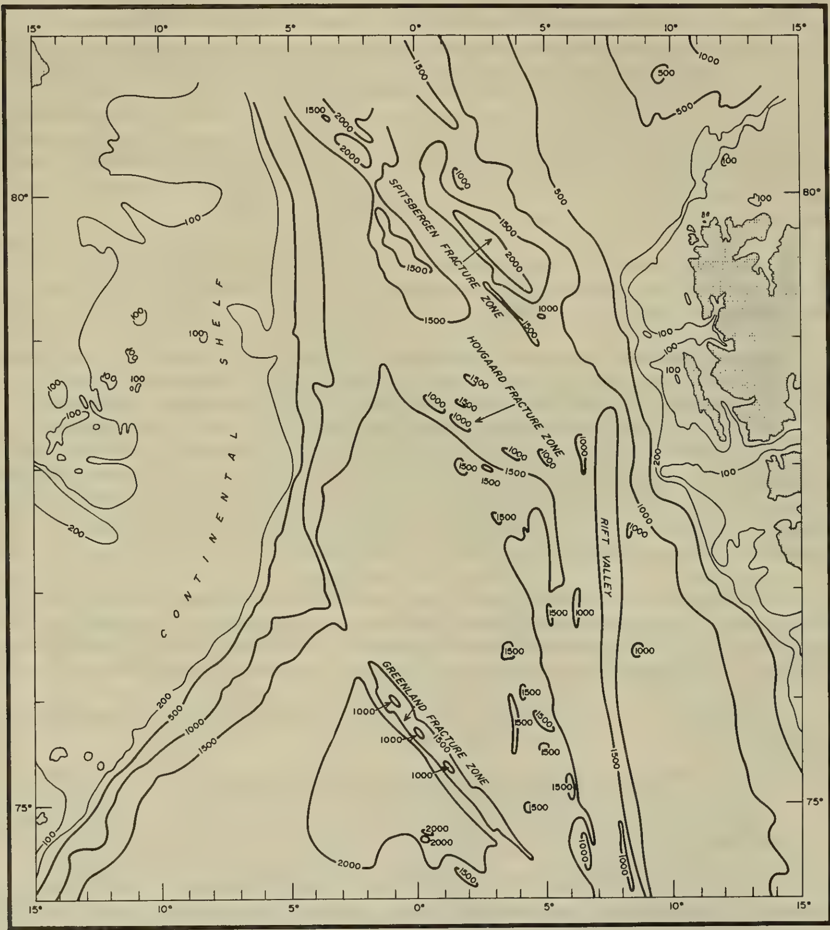

Figure 2. Bathymetry of the Northern Greenland Sea. Depths Are in Nominal Echo-Sounding Units of 1/400 Sec. Travel Time.

Among the more important bathymetric features of the northern Greenland Sea are the extension of the Mid-Oceanic Ridge with its associated rift-valley which lies slightly to the west of Svalbard and the Greenland, Hovgaard, and Spitsbergen fracture zones (Fig. 2).

For many years, it generally was considered that a relatively shallow sill (the Nansen Sill) with a maximum depth of approximately 1500 meters extended from northern Svalbard to Greenland and separated the deeper waters of the Greenland Sea from the Polar Basin (Nansen 1902, 1915, Sverdrup 1933, Sverdrup, Johnson and Fleming 1942). However, more recent hydrographic surveys indicate that such a sill probably does not exist. The shoalest barrier between the Greenland Sea and the adjacent Arctic Ocean now appears to be the Hovgaard Fracture Zone which lies to the south of the proposed region of the Nansen Sill. Lationov, Shamontev, and Yanes (1960) feel that the maximum depths of this barrier are on the order of 3000 meters, and Johnson and Eckhoff (1966) believe that the maximum sill depth is not less than 2600 meters. The deepest saddle in this sill appears to lie between the western extremities of the Hovgaard Fracture Zone and the Greenland Continental Slope.

2. Some Climatic Factors.

According to the Air Weather Service (1946), mean monthly surface air temperatures in the survey area range from approximately -20°C in February to 2°C in August, and the annual precipitation in the region is approximately 250 mm/year. Zaitsev, Fedosov, Iljina, and Ermachenko (1961) claim that the annual evaporation in this region is also about 250 mm/year.

Winds at Danmarks Havn (76°46'N, 18°46'W), which is slightly to the southwest of the survey area, and at Nord (81°40'N, 17°50'W), which is somewhat to the northwest of the survey region, are usually less than 15 knots (Det Danske Meteorologiske Institut 1961). Severe sea and swell conditions do not frequent the survey region (U.S. Navy Hydrographic Office 1958).

3. The Ice Regime.

Surface currents create a distinctive ice distribution in the survey region. In the western sector, the East Greenland Current carries approximately 2000 km^3 of ice out of the Arctic Ocean every year (Timofeev 1958, Lationov _et al_. 1960, Mosby 1962), and as a consequence, this region usually has a heavy ice cover (Fig. 3). Except for the more northerly portions of the survey area and the portions which are close to Svalbard, the eastern sector is usually ice-free because of the influence of the warm north setting West Spitsbergen Current.

Ice which is carried out of the Arctic Ocean by the East Greenland Current is usually several years old and hummocked. Its average

thickness is about two to three meters (Helland-Hansen and Nansen 1909). Except for any icebergs which might be encountered, the rest of the ice in the survey area usually will be less than a year old and will be completely melted during the summer (Lationov et al. 1960).

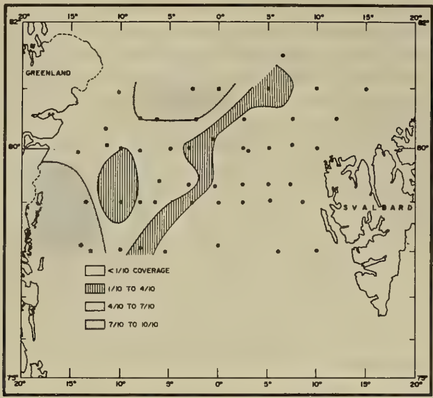

Figure 3. Ice Conditions Encountered by EDISTO in 1964.

4. Tides.

Tides in the northern Greenland Sea appear to be basically semidiurnal, and except for some nearshore regions, the spring tidal range is approximately one meter (U.S. Navy Hydrographic Office 1958).

IV. RESULTS OF PREVIOUS INVESTIGATIONS

Although only a small amount of data were available to them, many of the major oceanographic features of the Greenland Sea were correctly described by Helland-Hansen and Nansen (1909). According to them, the two major currents in the northern Greenland Sea were the West Spitsbergen Current (which they called the Spitsbergen Atlantic Current) which sets north close to the shores of Svalbard and the East Greenland Current which sets south close to the shores of Greenland (Fig. 4). They claimed that the East Greenland Current gives off an eastward branch north of Jan Mayen Island and that the West Spitsbergen Current divides near northern Svalbard, with one part moving westward and the other setting east into the Polar Basin. Thus, except for the eastward moving portion of the West Spitsbergen Current, their conception of the circulation of the upper layers of the Greenland Sea could be described loosely as a large cyclonic gyre (sometimes referred to as the Greenland Gyre). According to them, currents in the central regions of this cyclone were relatively sluggish and

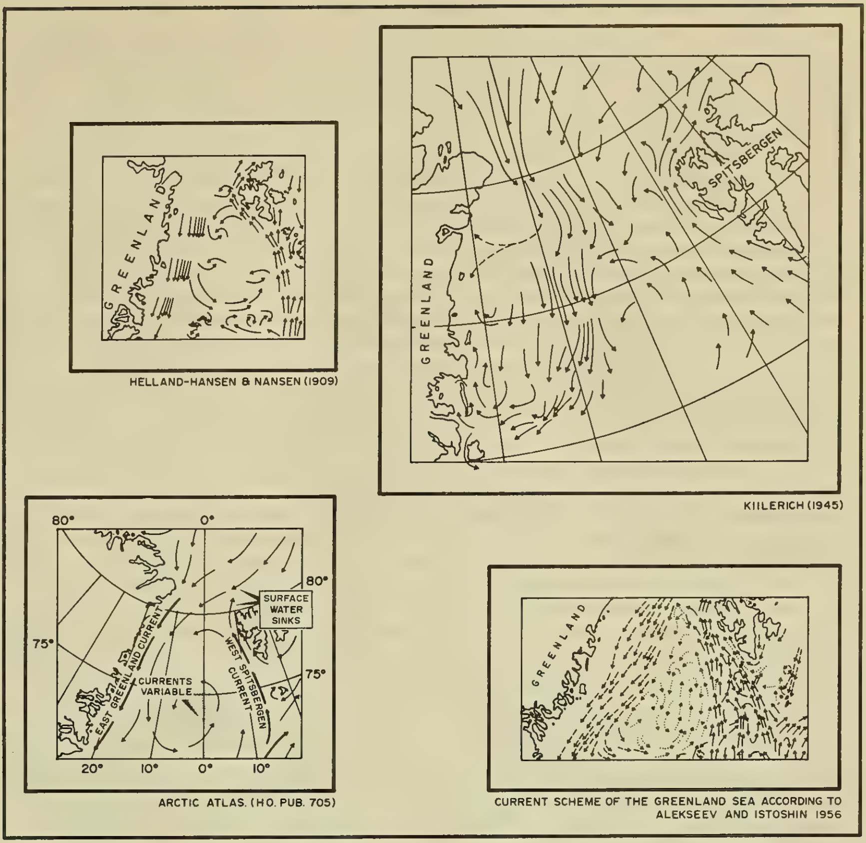

Figure 4. Current Schemes of Previous Investigators.

divided into a number of vortex movements. They believed that vortices were common throughout the region and pointed out that such movements may have been responsible for the waviness of the isopleths in many of their sections. Helland-Hansen and Nansen also described two additional features of the circulation of the Greenland Sea. One is the continuation of the East Spitsbergen Current which rounds southern Svalbard and flows north as a relatively small, cold, and dilute current between the West Spitsbergen Current and Svalbard. The other feature is the continuation of the western offshoots of the West Spitsbergen Current which flow slowly southward beneath the East Greenland Current and which is sometimes called the Return Atlantic Current.

Helland-Hansen and Nansen (1909) called the deep waters in the region with temperatures between 0° and -1.3°C and a nearly uniform salinity of about 34.92 ‰ Norwegian Sea Bottom Water. They describe this water mass as being formed by surface cooling and ice formation during the winter and claimed that it fills more than two-thirds of the volume of the Norwegian and Greenland Seas. They thought that a likely site for the formation of this water mass was in the central region of the Greenland Gyre and suggested that some might also form in a region between Jan Mayen Island and Iceland. In a later work, Nansen (1915) pointed out that there was no significant difference between salinities of the Norwegian Sea Bottom Water and the deep waters of the Polar Basin. This indicated that portions of the Norwegian Sea Bottom Water were flowing north and filling the basins of the Arctic Ocean. Nansen noted that minimum temperatures ($\approx$ -0.8° to -0.9°C) of the bottom waters of the Polar Basin were higher than those of the bottom water he found in the Norwegian and Greenland Seas ($\approx$-1.3°C). He said that this could be explained by mixing of the coldest bottom waters with warmer water or by the existence of a continuous ridge between Svalbard and Greenland with a sill depth of approximately 1500 meters. It should be remembered that he merely said that existence of such a ridge was a possibility. Erroneous salinity data had caused him to be more certain of the existence of this ridge in an earlier study (Nansen 1902). As mentioned above, recent data indicate that such a ridge does not exist.

Some of the views held by the above authors recently have been questioned. Whereas Helland-Hansen and Nansen (1909) believed that the bottom waters are carried to depth by an active vertical circulation, Metcalf (1955) claims that they sink by flowing along isopycnal surfaces only slightly inclined from the horizontal. He also (Metcalf 1960) has divided the bottom waters in the Greenland Sea into two masses, that formed in the Greenland Gyre and that formed in the Norwegian Gyre (a large cyclonic gyre found in the Norwegian Sea). According to him, at depths below 1500 meters the bottom waters formed in the Norwegian Gyre are always -0.97°C or warmer while the bottom waters formed in the Greenland Gyre are always colder than -0.99°C.

Various estimates have been made of velocities, transports, and fluctuations of the major currents in the northern Greenland Sea. Jackhelln (1936) and Kiilerich (1945) state that the East Greenland Current is strongest in the vicinity of the Greenland Continental Slope and that it attains maximum speeds of approximately 30 cm/sec. Lationov, et al. (1960) indicate that average speeds of this current between 0-100 meters are approximately 20 cm/sec in the northern Greenland Sea with maximum speeds occurring during the winter and minimum speeds occurring in inshore regions during the summer. The Return Atlantic Current is said to flow southward under the East Greenland Current with speeds of about 1 to 2 cm/sec (Chaplygin 1959). The speed of the West Spitsbergen Current at 77°N has been estimated to be about 5 to 15 cm/sec (Lationov et al. 1960), and its branch which turns to the east near northern Svalbard is estimated to have speeds of about 10 cm/sec (Sverdrup 1933).

The question of current transport in the northern Greenland Sea is of great importance. The warm, relatively high salinity water carried north by the West Spitsbergen Current is the primary component of the warm intermediate layer of the Arctic Ocean (the Atlantic Water), and the branches of this current which continue into the Arctic Basin appear to be its largest inflow. Mosby (1962) estimates the West Spitsbergen Current's contribution to the Arctic Ocean to be about 1.4×10^6 m^3/sec with the largest transports occurring in winter (November-February) and the lowest transports occurring in May. Kislyakov (1960) states that the mean transport of the West Spitsbergen Current from 1954-1959 for a section along 74°30'N was about 3×10^6 m^3/sec. According to him, the lowest annual transport derived from these sections occurred in 1955 and was about 0.8×10^6 m^3/sec, and the highest occurred in 1957 and was approximately 5×10^6 m^3/sec. Mosby (1962) estimates that flow of bottom waters from the Greenland Sea into the Arctic Basin is approximately 0.6 m^3/sec. Although some workers disagree (Zaitsev et al. 1961), it is generally accepted that the East Greenland Current represents the major outflow of the Arctic Ocean. Mosby (1962) estimates that it removes 2×10^6 m^3/sec, and Coachman (1962), in an examination of the literature, found estimates for its volume transport which ranged from 2.5×10^6 to 6×10^6 m^3/sec. Most of the ice transported out of the Arctic Ocean is carried south by the East Greenland Current. Lationov et al. (1960) estimate that its ice transport is about 1800 km^3/year, and Timofeev (1958) estimates it to be approximately 3100 km^3/year. Kiilerich (1945) claims that the volume transport of the Return Atlantic Current near 76°N is about 0.4×10^6 m^3/sec.

As the wide ranges of some of the above estimates indicate, knowledge of the volume transports of the currents in the northern Greenland Sea is rudimentary. Direct current measurements as well as oceanographic data for the winter months are rare. Dynamic calculations form the basis of many of the estimates, and it is not likely that such calculations are overly precise. The data are often not at all synoptic, and it is difficult to envisage a motionless reference level because of the movement of the deeper waters into the Arctic Basin.

There is some disagreement in the literature concerning the names and the salinity and temperature characteristics of the waters in the Greenland Sea. However, Helland-Hansen and Nansen's (1909) definition of Atlantic Water as any water with salinities greater than 35‰, and Jakhelln's (1936) definition of extreme Polar Water (Polar Water in its origin) as a water type with a salinity of 34.07‰ and a temperature of -1.85°C have found some acceptance. Helland-Hansen and Nansen's (1909) definition of Norwegian Sea Bottom Water (salinity close to 34.92 ‰ and temperature 0° to -1.3°C) also generally has been accepted. But if Metcalf's (1960) division of Greenland Sea bottom waters into two masses formed in different localities is correct, the name Norwegian Sea Bottom Water may give a mistaken impression of the origin of some of the bottom waters in the Greenland Sea.

In this report, the name Arctic Bottom Water, which Stefánsson (1962) has used, will be employed to describe all of the waters in the Greenland Sea with temperatures less than 0°C and salinities close to 34.91 ‰. Polar Water shall mean all waters with temperatures less than -1.50°C, and the term Atlantic Water will include all waters with salinities greater than 35 ‰.

In the Greenland Sea, the coldest Polar Water is normally found in the 'core' of the East Greenland Current, and Atlantic Water is found in the 'core' of the West Spitsbergen Current. The possible modes of Arctic Bottom Water formation already have been discussed.

Other water masses have been defined, but it seems most convenient to emphasize only the three described above. Properties of the remaining waters can be accounted for by assuming that they are mixtures of the three primary masses or that they represent the primary masses or their mixtures after modification by processes occurring at the surface such as ice formation and dilution by runoff and melting ice.

Although no thorough study of dissolved oxygen and micronutrient distributions in the northern Greenland Sea seems to have been made, some of the gross features have been described. Oxygen saturations have been found to be uniformly high (Lationov _et al_. 1960, Nansen 1915, Sverdrup 1933) seldom falling below 80% even in the deepest layers. Sverdrup (1933) found reactive phosphorus concentrations of 0.3 to 1.3 µg-at/liter in the waters adjacent to northern Svalbard. Reliable nitrate and reactive silicate data do not appear to be readily available for the northern Greenland Sea.

Recently, Russian scientists have conducted fairly comprehensive surveys of the northern Greenland Sea aboard LITKE (1955), OB (1956 and 1958), and LENA (1957), but the data from these cruises have not been made available.

V. DATA PRESENTATION

1. Salinity-Temperature Diagram.

Figure 5 shows the salinity-temperature relationships encountered in the 1964 EDISTO survey region. Among the features brought out by this diagram are the following:

a. The extreme Polar Water (salinity ≈ 34.07‰ , temperature ≈ -1.85°C) as defined by Jakhelln (1936) was not encountered. The salinity-temperature diagram indicates that any of this water type which may have been originally present had been altered by mixing with the warmer high salinity water which lies below and to the east of the East Greenland Current, or by the effects of runoff, ice-melt and heating at the sea surface.

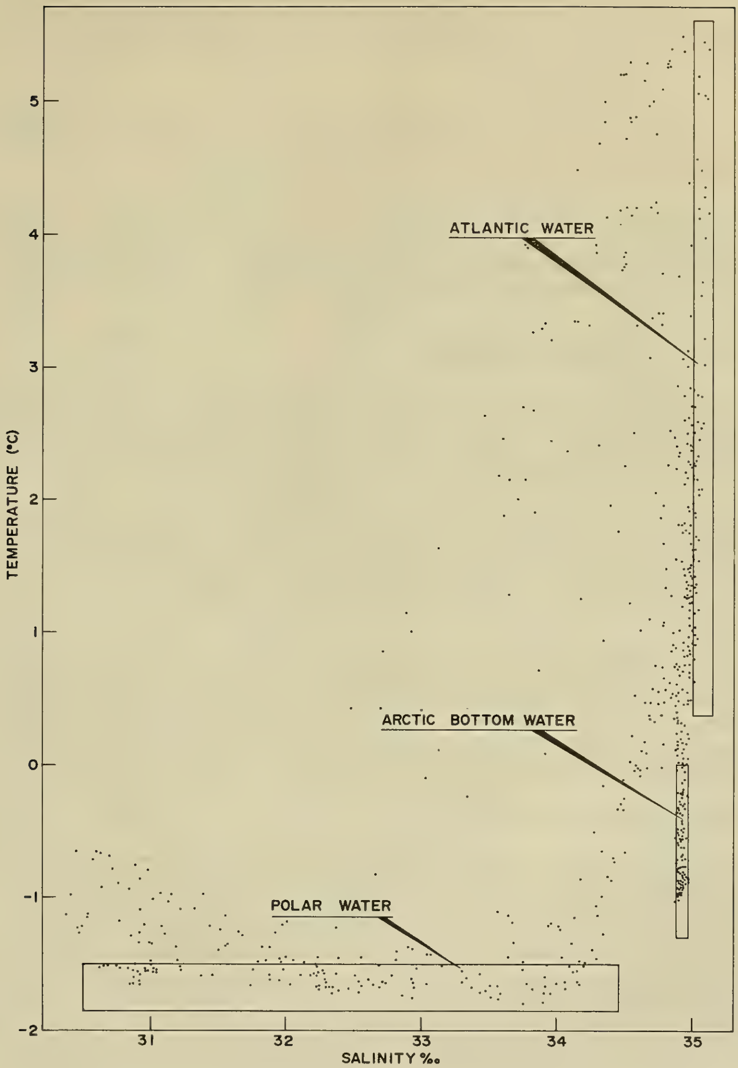

Figure 5. Salinity-Temperature Diagram Constructed From 1964 EDISTO Data.

b. Polar Water as defined in this report was frequently encountered. Mixing of this water mass with Arctic Bottom Water did not appear to be taking place, as is to be expected since Polar Water was found only in the upper layers.

c. Most of the Arctic Bottom Water was warmer than -0.98°C indicating that the EDISTO stations were too far north to include the 'core' of the bottom water formed in the Greenland Sea Gyre.

d. The wide range of temperatures in the Atlantic Water indicates that it gives up a good deal of its heat to the atmosphere because surface cooling is the most likely process which could cause a great reduction in temperature without causing a fairly large salinity change.

2. Temporal Variation Diagrams.

Stations 1 and 50 were occupied at approximately the same location but two weeks apart. Consequently, comparison of salinity, temperature, and density data from the two stations (Fig. 6) yields useful information concerning temporal variations in water properties.

Density changes in the upper 100 meters were relatively small compared to the salinity and temperature differences. This indicates that the salinity and temperature changes compensated for each other, to a certain extent, as far as density was concerned.

Large temporal variations should be expected in the upper layers of the water column at this location because the properties of the upper layers will be modified not only by variations in the West Spitsbergen Current and by climatic factors, but also by variations in the continuation of the cold and dilute East Spitsbergen Current and changes in the temperature and volume of runoff from Svalbard.

3. Vertical Sections.

Because temperature and concentration gradients were more pronounced in the upper layers of the water column, the vertical sections (Figs. 7 though 11) were drawn with a divided depth scale. The vertical exaggeration above 300 meters is about 350 to 1, four times greater than for the rest of the water column. Since the oceanographic stations were numbered consecutively in the order in which they were occupied, a large numerical difference between adjacent stations in a section indicates that they were separated by a relatively large time interval. This should be taken into account when interpreting the sections because they were contoured just as if the data were synoptic.

Certain gross features are common to most of the sections. These include:

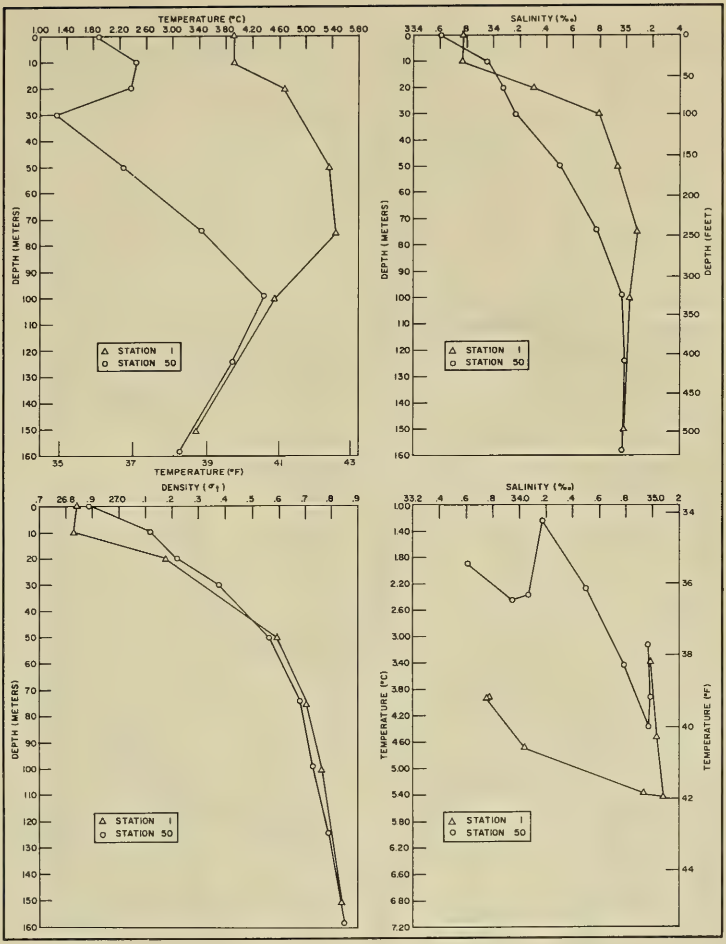

Figure 6. Temporal Variation Diagrams.

a. The presence of a 0°C isotherm between 500 and 900 meters below which the enormous volume of waters with the uniform salinities characteristic of Arctic Bottom Water was found;

b. A sharp decrease in salinity as the coast of Greenland is approached;

c. The presence of Polar Water at depths between 0 and 150 meters in the western portions of the sections with the coldest Polar Water often found close to the region where the horizontal temperature gradients were the greatest;

d. The presence of a relatively warm intermediate layer beneath the Polar Water resulting from the westward transport of Atlantic Water and indicating the presence of the Return Atlantic Current;

e. The presence of Atlantic Water in the eastern portions of the sections at depths between 50 and 500 meters[1];

f. High oxygen saturations throughout the water column;

g. A tendency for micronutrient concentrations to increase with depth;

h. An increase in reactive phosphorus concentrations in the upper 50 meters as the coast of Greenland is approached.

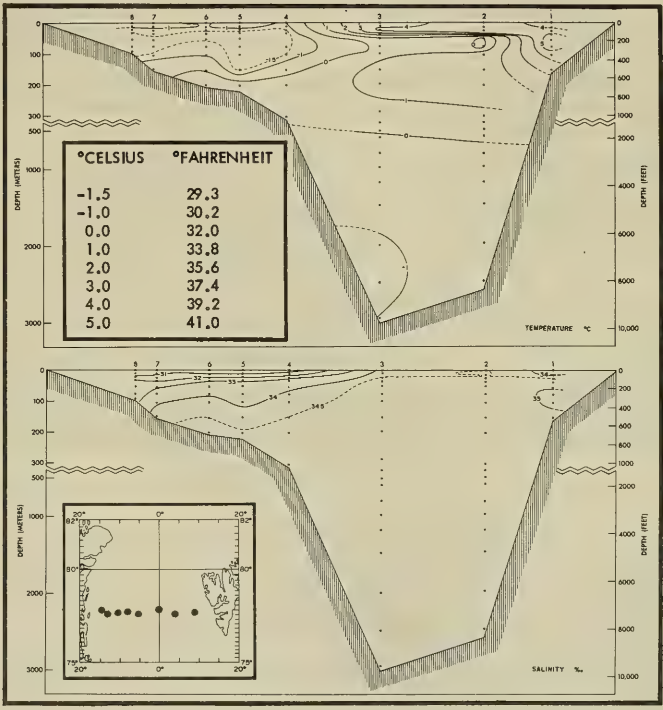

Figure 7A. Vertical Distributions of Temperature and Salinity For Cross Section of Stations 8 to 1.

---

[1] When present, Polar Water and Atlantic Water would lie within these depth ranges. They would not necessarily occupy the entire depth range.

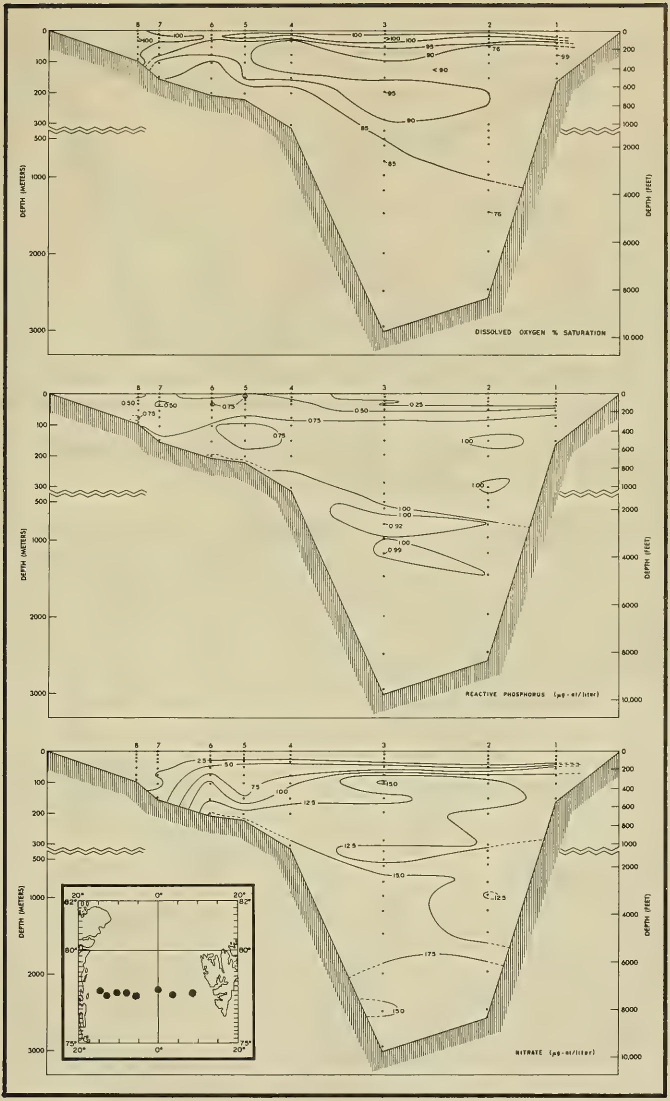

Figure 7B. Vertical Distributions of Dissolved Oxygen Saturation, Reactive Phosphorus, and Nitrate For Cross Section of Stations 8 to 1.

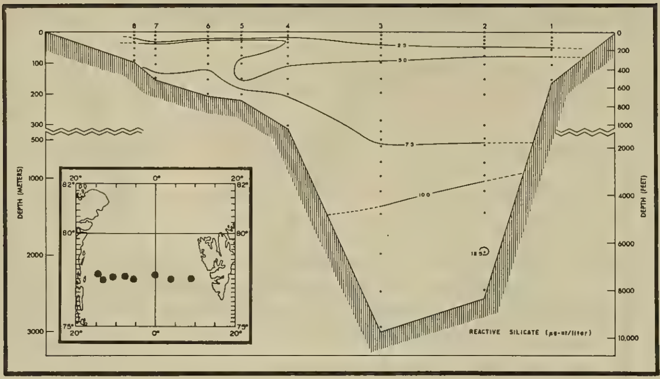

Figure 7C. Vertical Distribution of Reactive Silicate For Cross Section of Stations 8 to 1.

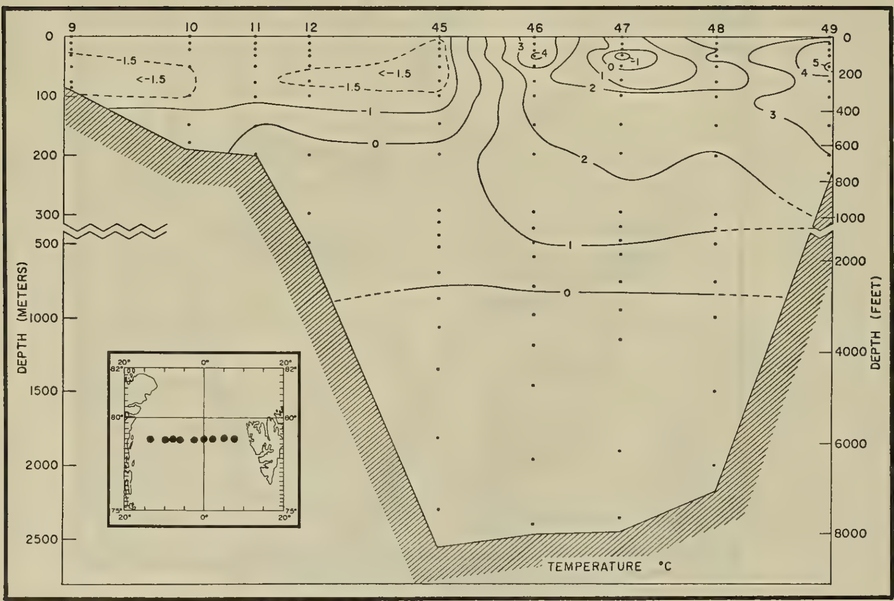

Figure 8. Vertical Distribution of Temperature For Cross Section of Stations 9 to 49.

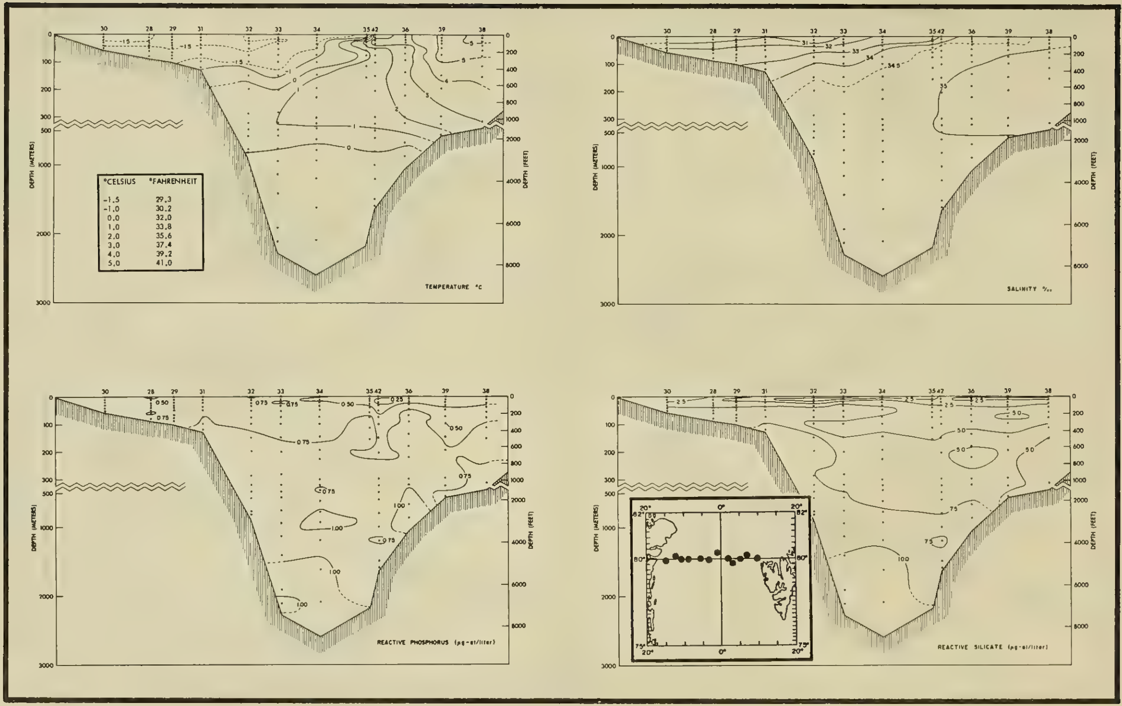

Figure 9. Vertical Distributions of Temperature, Salinity, Reactive Phosphorus, and Reactive Silicate For Cross Section of Stations 30 to 38.

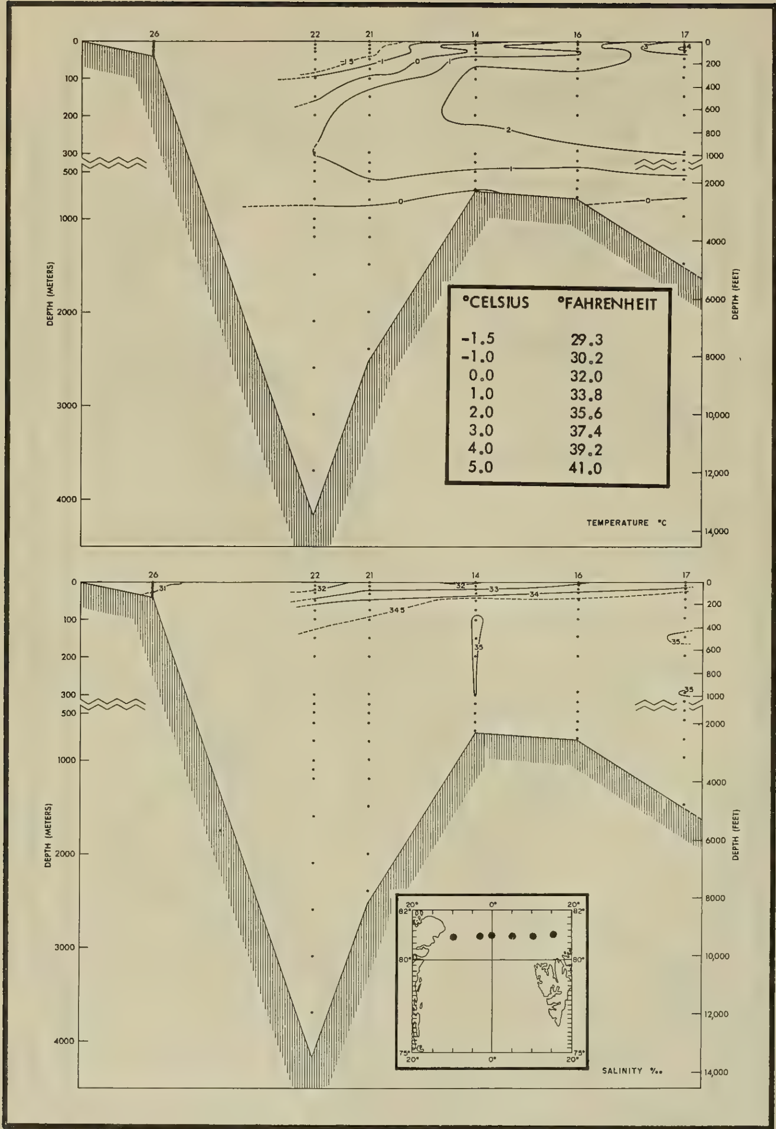

Figure 10A. Vertical Distributions of Temperature and Salinity For Cross Section of Stations 26 to 17.

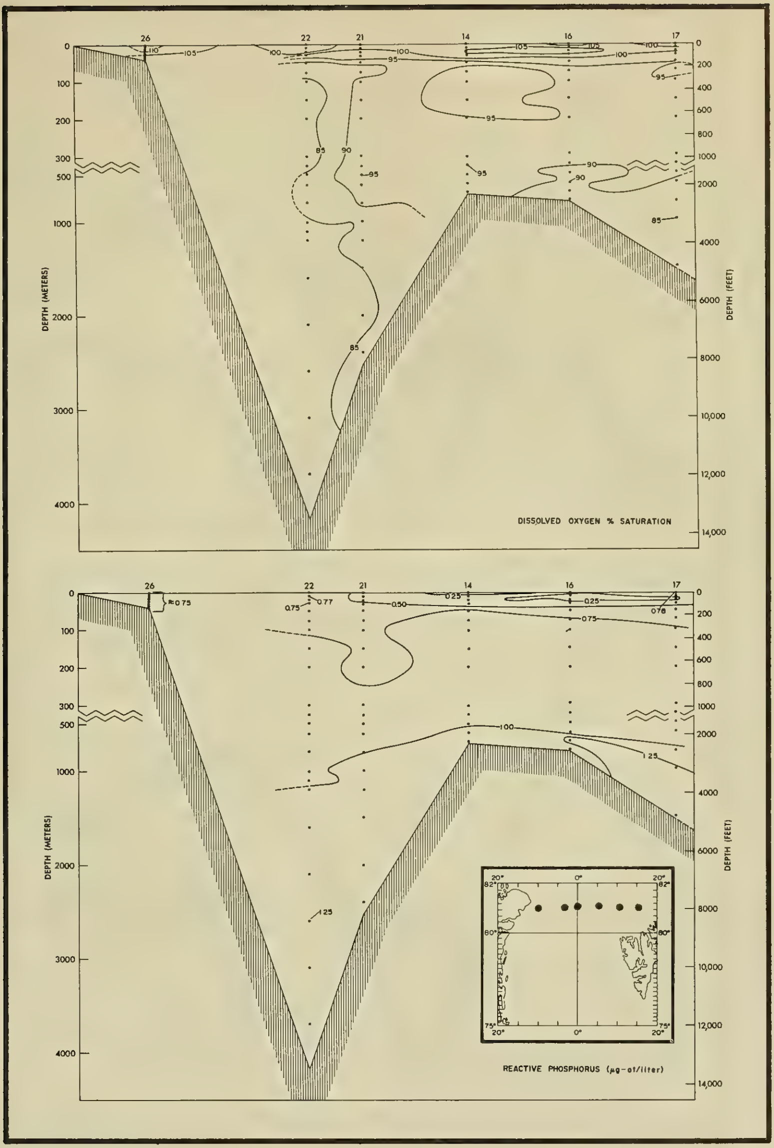

Figure 10B. Vertical Distributions of Dissolved Oxygen Saturation and Reactive Phosphorus For Cross Section of Stations 26 to 17.

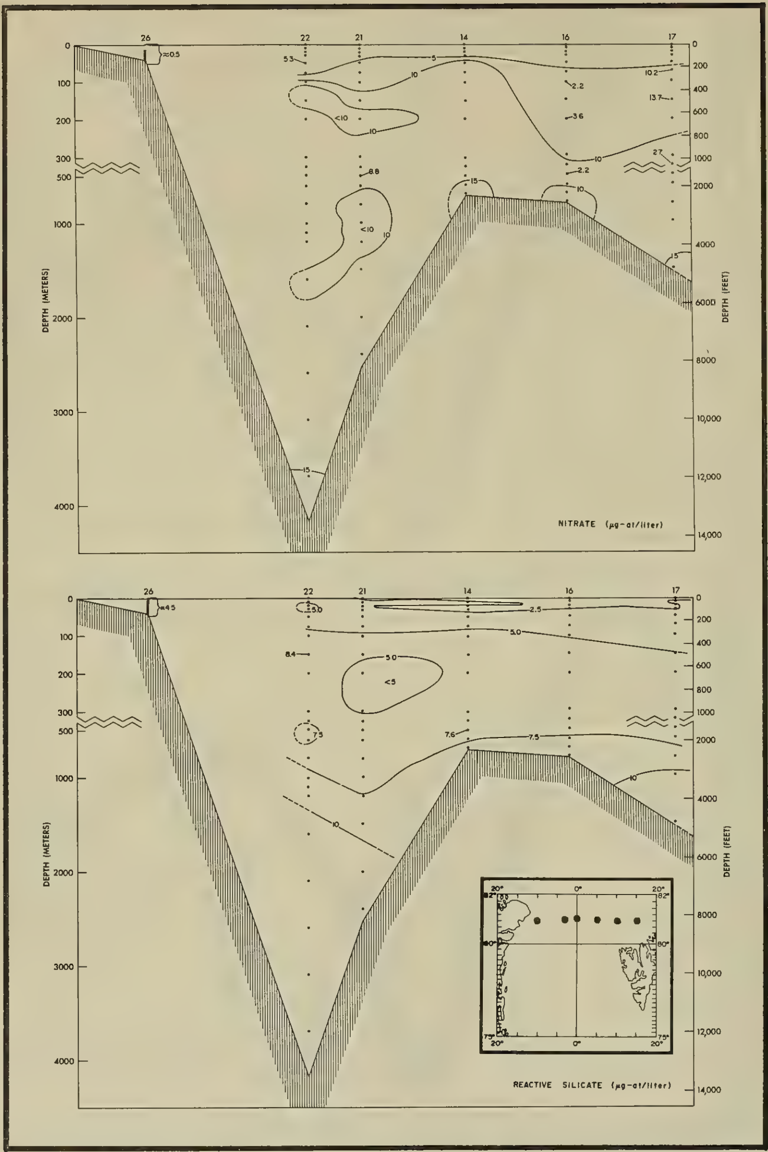

Figure 10C. Vertical Distributions of Nitrate and Reactive Silicate For Cross Section of Stations 26 to 17.

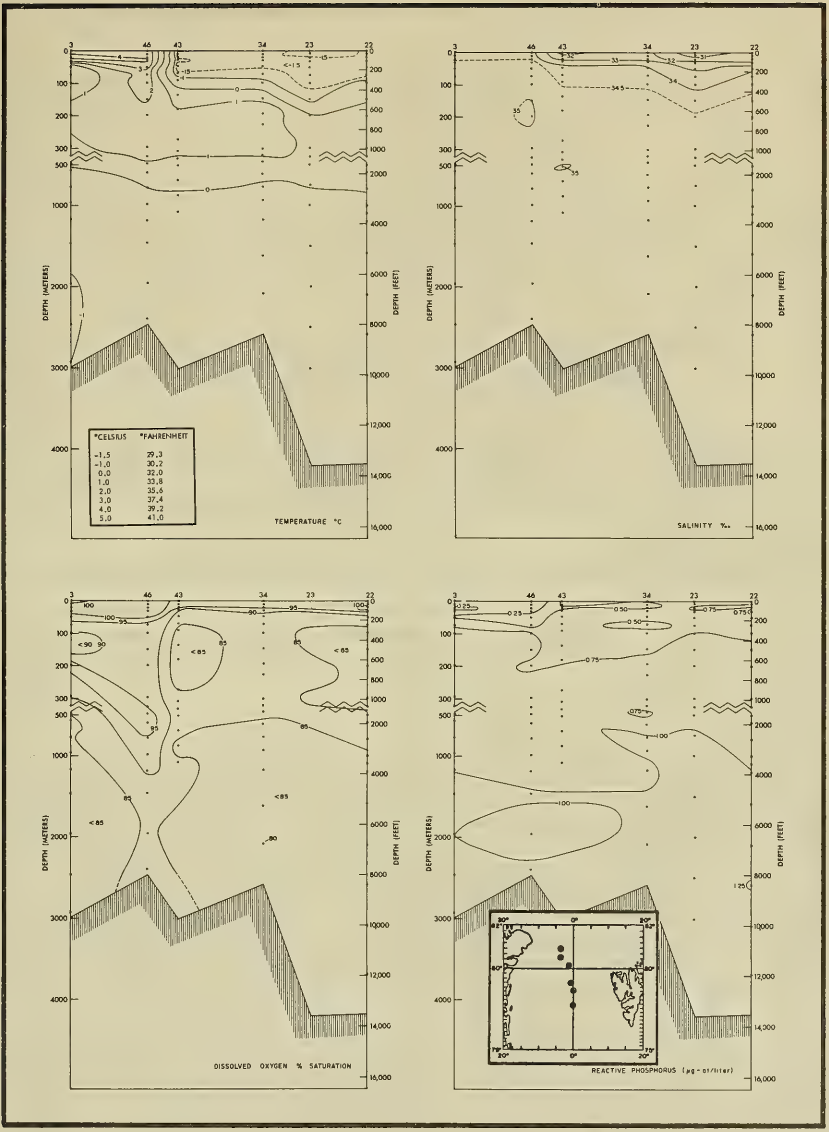

Figure 11A. Vertical Distributions of Temperature, Salinity, Dissolved Oxygen Saturation, and Reactive Phosphorus For Cross Section of Stations 3 to 22.

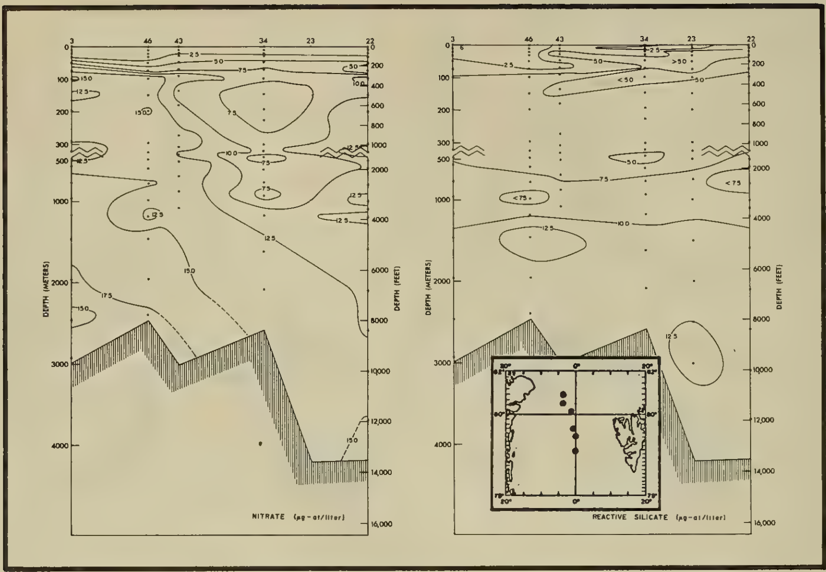

Figure 11B. Vertical Distributions of Nitrate and Reactive Silicate For Cross Section of Stations 3 to 22.

4. Horizontal Charts.

Figures 12 through 25 present the horizontal distribution of salinity and temperature at various levels. When data from an observation depth did not correspond to a selected level, interpolated data were used. As in the case of the vertical sections, the data were contoured as if they were synoptic. Consequently, the 'pinched' nature of some of the isopleths between stations 35 and 42 may be partially due to their being occupied 1 1/2 days apart. Only stations for which data were available to the depth of a given level have been indicated on the charts depicting conditions at that level. Although stations 1 and 50 were taken at approximately the same location, only the data from station 1 were used in constructing these diagrams.

A. <u>0-and 10-meter levels</u>: Conditions at 0 and 10 meters (Figs. 12 through 15) were quite similar. Perhaps the most outstanding feature at these depths was the thermal 'front' (sometimes called the Polar Front) found in the central and western portions of the survey region. This 'front' marks the boundary between the warm waters carried north by the West Spitsbergen Current and the cold waters of the East Greenland Current. The waviness of the isotherms suggests the presence of large meanders or vortices.

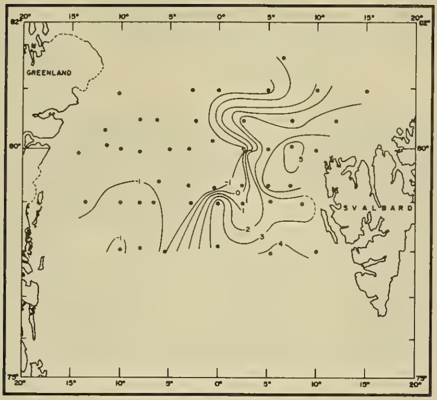

Figure 12. Horizontal Temperature Distribution at 0 Meters. Contour Interval – 1°C.

Figure 13. Horizontal Salinity Distribution at 0 Meters. Contour Interval – 1‰ .

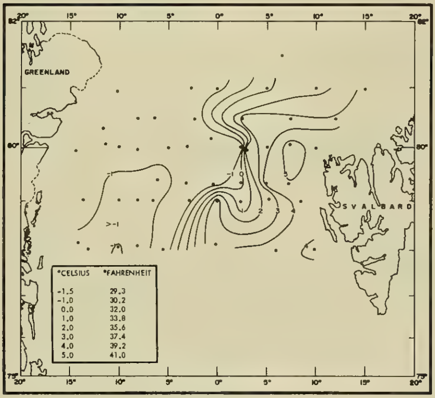

Figure 14. Horizontal Temperature Distribution at 10 Meters. Contour Interval – 1°C.

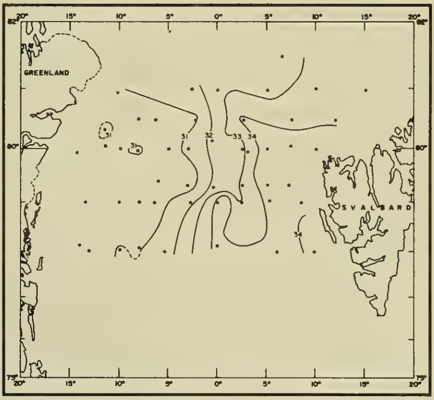

Figure 15. Horizontal Salinity Distribution at 10 Meters. Contour Interval – 1‰.

To the west of the Polar Front, temperatures were cold (<0°C) and fairly uniform. To the east, temperatures increased to maximum values and then tended to decrease slightly in some localities in the vicinity of Svalbard. These reduced temperatures probably reflect the influence of runoff, ice-melt, and the continuation of the East Spitsbergen Current.

The isotherms at 0 and 10 meters were duplicated to a large extent by the isohalines. Sharp horizontal salinity gradients were found in the vicinity of the Polar Front with salinities tending to increase with increasing temperature. The region of relatively uniform horizontal temperature distribution to the west of the Polar Front also was a region of fairly uniform horizontal salinity distribution.

B. <u>50-meter level</u>: Only a temperature diagram (Fig. 16) is presented for the 50-meter level. The gross features are similar to those found at 0 and 10 meters; however, there are some differences. Temperatures close to Svalbard were warmer, and waters to the west of the Polar Front were slightly colder at the 50-meter level. In the southern part of the survey region, maximum temperature gradients were found farther east, and the configuration of the vortex or meander indicated by the isotherms is considerably different. Near 80°N, horizontal temperature gradients were not as marked at 50 meters as they were at 0 and 10 meters.

Isotherms in the northern part of the survey region indicate that a large stream of the West Spitsbergen Current turns east in this region.

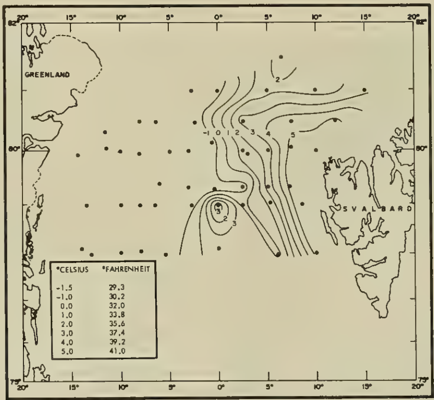

Figure 16. Horizontal Temperature Distribution at 50 Meters. Contour Interval — 1°C.

C. 100-meter level: A thermal 'front' was still present at 100 meters, but the horizontal temperature gradients were weaker, and shapes of the isotherms (Fig. 17) were often quite different than at 0, 10, and 50 meters. The -1°C isotherm indicates that at this level relatively warm water may be flowing into the western portion of the survey region from the northeast.

Salinities at 100 meters (Fig. 18) displayed the same tendency to decrease towards the west as was found at 0 and 10 meters. However, the maximum horizontal salinity gradients were not as great as those in the upper levels, and the largest gradients were found west of the Polar Front.

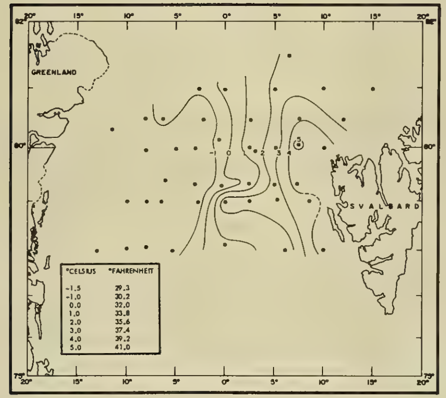

Figure 17. Horizontal Temperature Distribution at 100 Meters. Contour Interval – 1°C.

Figure 18. Horizontal Salinity Distribution at 100 Meters. Contour Interval – 0.5‰.

D. 200-meter level: One of the more interesting aspects of the temperature distribution at 200 meters (Fig. 19) is that all of the temperatures are greater than 0°C. Since the boundary between the cold waters of the East Greenland Current and the relatively warm waters of the Return Atlantic Current is usually taken to be the 0°C isotherm, it is clear that this boundary was between 100 and 200 meters throughout the entire survey region.

Maximum temperatures were again found close to Svalbard, but they were noticeably colder than at 50 and 100 meters, indicating that the 'core' of the West Spitsbergen Current probably lay above the 200-meter level. As in the upper layers, a strong tendency for isotherms to turn east near northern Svalbard can be noticed.

Salinity (Fig. 20) and temperature ranges at this level were considerably less than those in the upper levels.

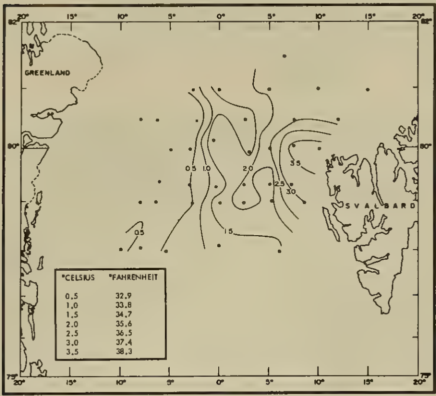

Figure 19. Horizontal Temperature Distribution at 200 Meters. Contour Interval – 0.5°C.

Figure 20. Horizontal Salinity Distribution at 200 Meters. Contour Interval – 0.1‰.

E. <u>500-meter level</u>: The shapes of the isotherms and isohalines (Figs. 21 and 22) were similar in many respects to those in the 200 meter level, but conditions were much more uniform. Again, all temperatures were greater than 0°C indicating that the Arctic Bottom Water lay below this depth throughout the survey region when the 1964 EDISTO stations were occupied.

Figure 21. Horizontal Temperature Distribution at 500 Meters. Contour Interval – 0.5°C.

Figure 22. Horizontal Salinity Distribution at 500 Meters. Contour Interval – 0.05‰.

F. <u>1000-meter level</u>: Compared to the levels above, the temperature regime at 1000 meters (Fig. 23) was considerably different. All temperatures were less than 0°C, and the coldest temperatures were found in the southeast portion of the survey region instead of decreasing towards the west.

The temperature range was relatively small (≈0.5°C), and the salinity range (Fig. 24) was a mere 0.08 ‰ reflecting the presence of the cold (<0°C), virtually isohaline Arctic Bottom Water at this level.

The increase in temperatures towards the west could be a reflection of mixing with the warmer waters of the Return Atlantic Current.

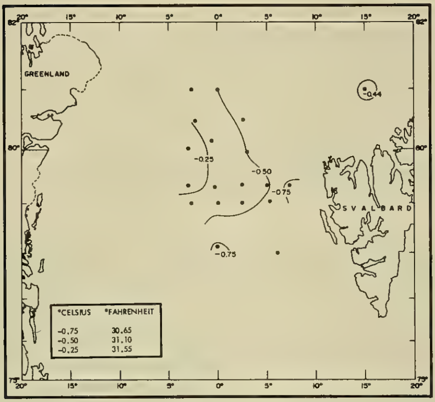

Figure 23. Horizontal Temperature Distribution at 1000 Meters. Contour Interval – 0.25°C.

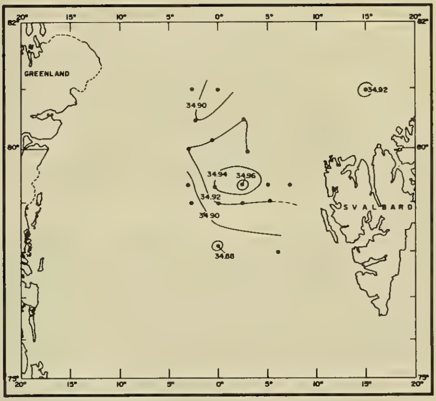

Figure 24. Horizontal Salinity Distribution at 1000 Meters. Contour Interval – 0.02‰.

G. <u>2000-meter level</u>: Only a temperature diagram (Fig. 25) is presented for this level. The temperature distribution is similar to that found at 1000 meters except that temperatures are colder (the lowest temperature was -1.01°C) and more uniform. When proceeding in a longitudinal direction, there was a tendency for temperatures to reach maximum values at about 80°N, and the coldest temperature was encountered at station 3 in the southernmost portion of the survey region.

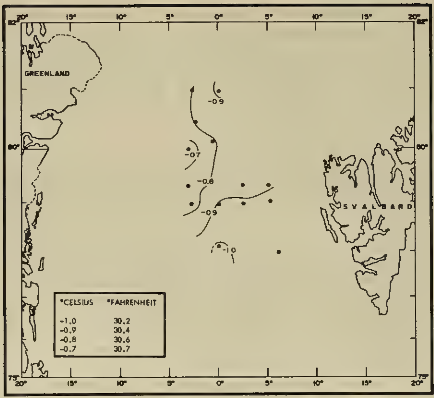

Figure 25. Horizontal Temperature Distribution at 2000 Meters. Contour Interval – 0.1°C.

5. Dynamic Topography.

Figures 26 through 35 show the current systems in portions of the survey region as determined from dynamic computations.

The method of Defant (1961) was used to select a reference level. The 700-decibar surface appeared to be the best choice (Figs. 26 through 31) although the data indicated that it was far from perfect. Other levels, such as the 1000-decibar surface, also appear to be acceptable, but the use of a deeper level would have reduced the number of stations which could be included. Three charts using a 1000-decibar reference level were constructed (Figs. 32 through 34), and they are presented here for comparison. In those locations which overlapped, the charts employing the 700-decibar reference surface and the charts using the 1000-decibar reference level were quite similar.

Stations for which observations did not exist to the selected reference level are not shown on the dynamic topography charts, and the dynamic computations were not extended into shallow water.

As shown above, the accuracy of the temperature and salinity measurements made during the 1964 EDISTO survey were probably about ±0.02°C (or less) and approximately ±0.02‰, respectively. In cold waters, temperature errors of about ±0.02°C will have only a small affect on dynamic computations. If there was a systematic error in salinities of about ±0.02 ‰ between stations, then with a reference level of 700-decibars, differences in dynamic heights at the surface could hardly be significant unless they exceeded 1 dynamic centimeter (Stefánsson 1962).

Directions of currents indicated by the dynamic topography charts did not change significantly with depth, but, as is usually the case, current speeds decreased as the reference level was approached.

Because many of the stations were too shallow to be included in the charts obtained by using a 700-decibar reference level, a surface current chart was constructed using a 200-decibar reference level (Fig. 35). This was done in the hope that a qualitative notion of the current regime at some of the more shallow stations could be obtained. Although speeds were not as great in regions where the charts overlapped, currents depicted by Figure 35 were similar to those shown on the surface current charts resulting from the choice of a 700- and 1000-decibar reference levels. This, together with the fact that maximum density gradients were found in the upper layers (note the changes in dynamic height gradients with increasing depth in Figures 26 through 31), indicate that the current regime shown by Figure 35 might be reasonably representative.

Maximum speeds in the portion of the East Greenland Current depicted by Figures 26 through 35 appear to be about 15 to 20 cm/sec. The West Spitsbergen Current and a westward branch which may merge with the Return Atlantic Current are indicated on the dynamic current charts, but the branch of the West Spitsbergen Current which turns eastward near northern Svalbard is indicated only on the 200-decibar reference level chart. In the portions of the West Spitsbergen Current shown by the dynamic topography charts, speeds did not appear to exceed 10 cm/sec.

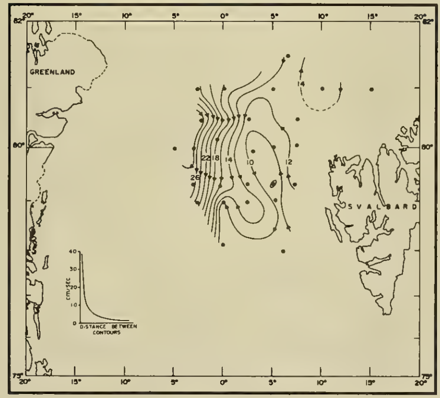

Figure 26. Dynamic Topography, 0-Decibar Surface and 700-Decibar Reference Level. Contour Interval – 2 dyn.cm.

Figure 27. Dynamic Topography, 10-Decibar Surface and 700-Decibar Reference Level. Contour Interval – 2 dyn.cm.

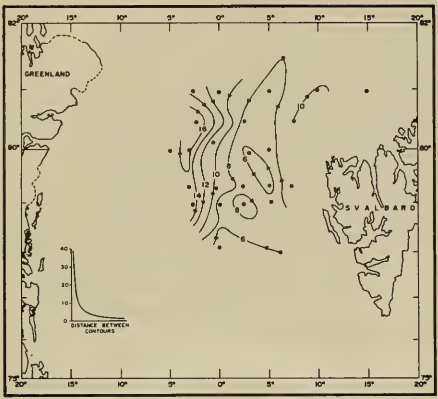

Figure 28. Dynamic Topography, 50-Decibar Surface and 700-Decibar Reference Level. Contour Interval – 2 dyn.cm.

Figure 29. Dynamic Topography, 100-Decibar Surface and 700-Decibar Reference Level. Contour Interval – 2 dyn.cm.

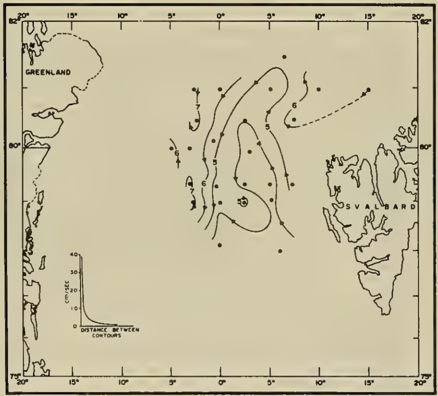

Figure 30. Dynamic Topography, 200-Decibar Surface and 700-Decibar Reference Level. Contour Interval – 1 dyn.cm.

Figure 31. Dynamic Topography, 500-Decibar Surface and 700-Decibar Reference Level. Contour Interval – 0.5 dyn.cm.

Figure 32. Dynamic Topography, 0-Decibar Surface and 1000-Decibar Reference Level. Contour Interval – 2 dyn.cm.

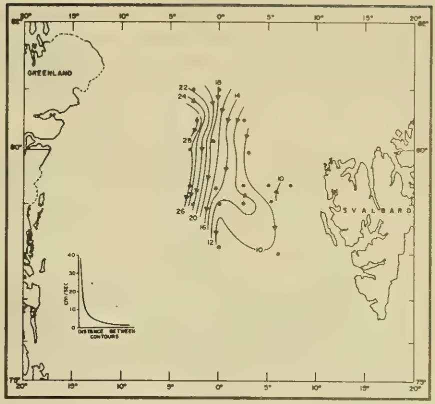

Figure 33. Dynamic Topography, 10-Decibar Surface and 1000-Decibar Reference Level. Contour Interval – 2 dyn.cm.

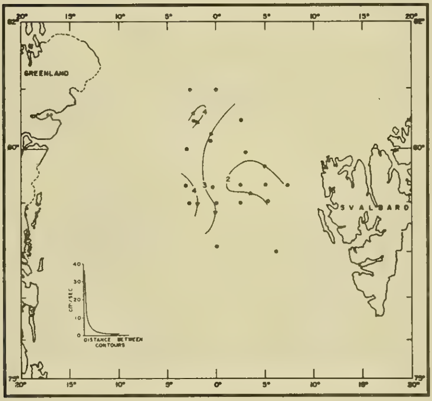

Figure 34. Dynamic Topography, 500-Decibar Surface and 1000-Decibar Reference Level. Contour Interval – 1 dyn.cm.

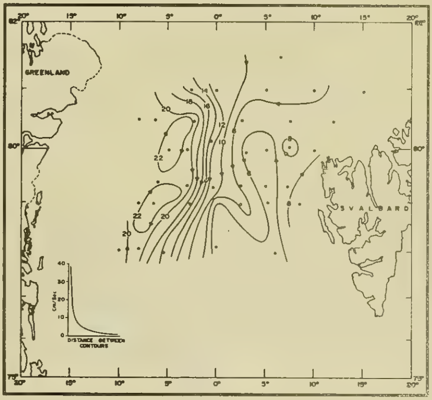

Figure 35. Dynamic Topography, 0-Decibar Surface and 200-Decibar Reference Level. Contour Interval – 2 dyn.cm.

Figures 26 through 35 indicate the presence of two large counter rotating gyres between the East Greenland and West Spitsbergen Currents. In the extreme northeast portion of the survey region, there are indications of a large anticyclonic gyre. Anticyclonic gyres also appear to be present to the west of the portion of the East Greenland Current shown on these charts.

The dynamic topography charts derived from the 1964 EDISTO data are, of course, subject to all of the normal and well known limitations of this type of current analysis.

6. Scatter Diagrams.

Two micronutrient versus micronutrient (Figs. 36 and 37) and three micronutrient versus temperature diagrams (Fig. 38) were constructed in an attempt to further summarize and organize the micronutrient data collected during this survey. The micronutrient versus temperature diagrams were constructed using data from the upper 50 meters only. The scatter diagrams will be discussed in more detail in the next section. For the present, it will suffice to point out that some of the scatter and overlap in these diagrams would not be present if more precise analytical techniques had been available. The nitrate values appear to be the least reliable micronutrient data, and some points were not included in Figure 37 because their nitrate values appeared to be suspiciously low.

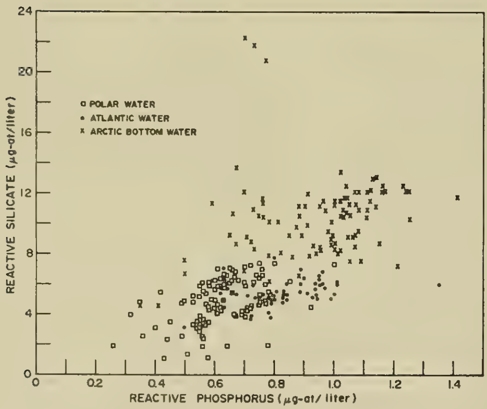

Figure 36. Reactive Silicate Versus Reactive Phosphorus.

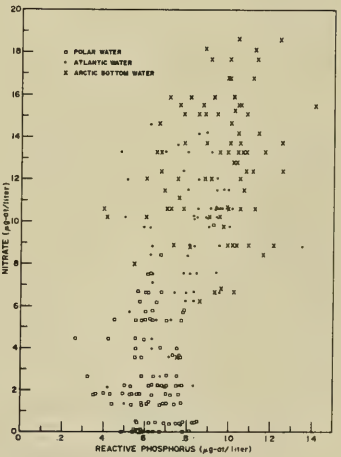

Figure 37. Nitrate Versus Reactive Phosphorus.

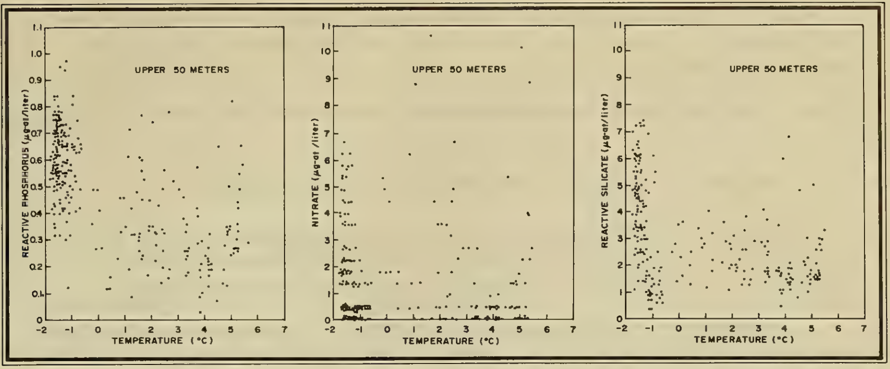

Figure 38. Micronutrients Versus Temperature For the Upper 50 Meters.

VI. DISCUSSION

1. General.

It is clear from the data presentation that results of the 1964 EDISTO survey tend to confirm many of the present ideas concerning the gross features of the oceanography of the northern Greenland Sea and adjacent Arctic Ocean. This in itself is important because most of the earlier investigations were based on few data. Data from this survey also point out some new aspects of the oceanography of the northern Greenland Sea and, in some cases, suggest that earlier concepts should be modified.

2. Currents.

Dynamic topography charts (Figs. 26 through 35) prepared from the 1964 EDISTO data give the impression that the western boundary of the East Greenland Current and in some localities its eastern boundary lay farther east than indicated on some previous charts (Fig. 4). In these respects and also in the shape of the southernmost anticyclonic gyre, the dynamic topographies look most like the current scheme presented by Kiilerich (1945).

On the chart based on the 200-decibar reference level, two anticyclonic gyres appear to the west of the indicated portion of the East Greenland Current, and indications of such gyres also appear on the charts resulting from the choice of deeper reference levels. Thus, it appears that the dynamic topography charts sometime extended far enough towards Greenland to include the western boundary of the East Greenland Current. It must be admitted that this impression could be erroneous since:

a. The East Greenland Current could have been divided into more

than one stream in the EDISTO survey region, and it is possible that there was an inshore portion which was not included in the dynamic topography charts.[2]

b. The barotropic components of the currents have not been estimated, and

c. Figure 35 employs such a shallow reference level.

Factors which indicate that the dynamic topography charts may have included the western boundary of the East Greenland Current throughout a good portion of the EDISTO survey region include:

a. Except for the 100 meter level (Fig. 18), the maximum salinity gradients[3] indicated by the horizontal charts for the upper 500 meters (Figs. 13, 15, 18, 20, and 22) were located in approximately the same region as the portion of the East Greenland Current displayed by Figures 26 through 35.

b. The existence of anticyclonic gyres to the west of the indicated portion of the East Greenland Current appears to be corroborated by the salinity distributions shown in Figures 18 and 20.

c. If the anticyclonic gyres in question do exist, any important stream of the East Greenland Current not included in the dynamic topography charts would have to exist as a separate stream running fairly close to shore. Yet, the inshore currents in summer are said to be weak (Lationov, et al., 1960).

The dynamic topography charts give the impression that the West Spitsbergen Current was not well developed during the time of the EDISTO survey. However, it is likely that these charts do not include a significant nearshore portion of this current. In addition, (see Section IV), it is difficult to envision a completely motionless reference level in the northern Greenland Sea. Since the suspected motion of the bottom waters under the West Spitsbergen Current is towards the north, a slow northward movement in the 700-and 1000-decibar reference levels may have caused the speeds of the West Spitsbergen Current as depicted by Figures 26 through 35 to be slightly lower than they really were.

The meanders and gyres between the East Greenland Current and the West Spitsbergen Current indicated by the dynamic topography charts also appear to be somewhat different than those shown on the charts of previous investigators (Fig. 4). To some extent this

---

[2] The original oceanographic log sheets for stations 28 and 29, which were close to Greenland, contain notes stating that strong currents were observed. However, the directions of these currents are not noted, and no estimate was made of their variability.

[3] In this region, density gradients are effected much more by salinity changes than by temperature changes.

is to be expected since such features often change considerably with time.

It should be kept in mind that the dynamic topography charts are based on data collected over a short period of time, and therefore it is quite possible that some of the current schemes presented by earlier workers may be more representative of average conditions. As Figure 6 shows, large temporal variations can occur within the survey region.

3. Salinity and Temperature Distributions in Arctic Bottom Water.

Salinities in the nearly isohaline bottom waters were not appreciably different than those encountered in the early part of the century. However, a comparison of the temperatures encountered by the BELGICA in 1905 (Duc D'orleans 1907) with those encountered in 1964 indicates that within the EDISTO survey area, minimum temperatures in the Arctic Bottom Water were lower at the time of the BELGICA cruise.[4] Also, when nearby stations were compared (Table II), there was a tendency

TABLE II. Comparison of Arctic Bottom Water Temperatures Found at BELGICA (1905) and FARM (1910) Stations with Those Found at Nearby EDISTO (1964) Stations

Station	Lat.°N	Long.	Temperature in °C			
			800m	1200m	1594m	1800m
BELGICA-15	80°03'	2°47'E	-0.14°	-0.72°	------	-1.06°
EDISTO-42	79°58'	3°00'E	0.03°	-0.77°	-0.97°	-------
			800m	1200m	1800m	2392m
BELGICA-17	79°34'	2°40'E	0.00°	-0.70°	-0.95°	-------
EDISTO-41	79°20'	2°30'E	0.21°	-0.55°	-0.84°	-0.87°
			800m	1200m	1800m	2350m
BELGICA-18	79°12'	1°52'E	-0.28°	-0.74°	-0.95°	-------
EDISTO-47	79°00'	2°30'E	0.05°	-0.59°	-0.86°	-0.93°
			800m	1200m	1800m	2300m
BELGICA-19	78°43'	0°00'	-0.34°	-0.71°	-1.10°	-1.17°
EDISTO-46	79°00'	0°00'	0.01°	-0.61°	-0.87°	-0.93°
			800m	1200m	1500m	2300m
FARM-21	78°08'	0°35'W	-0.57°	-0.93°	-1.04°	-1.19°
EDISTO-3	78°08'	0°00'	-0.56°	-0.88°	-0.97°	-1.01°
			800m	1200m		
FARM-18	79°03'	5°02'E	-0.59°	-1.02°		
EDISTO-48	78°40'	5°08'E	-0.02°	-0.81°		

[4] Within the EDISTO survey region, the minimum bottom water temperature encountered by the BELGICA was ≈-1.25°C, whereas the coldest bottom water temperature found during the EDISTO survey was -1.01°C.

for the Arctic Bottom Water at a given depth to be colder during the BELGICA cruise and during the cruise of H.M.S. FARM in 1910 (Helland-Hansen and Nansen 1912). These temperature differences could be a reflection of climatic changes, but further study is necessary to verify this.

Minimum Arctic Bottom Water temperatures found during a recent summer survey were approximately -1.10°C (Gladfelter 1964) and were encountered in the 'core' of the Arctic Bottom Water formed in the Greenland Gyre. Gladfelter has shown that the center of this formation lies at approximately 75°N and 0°, and this probably explains why the coldest bottom water temperatures were found in the more southerly portions of the EDISTO survey region (Figs. 11, 23, and 25).

Metcalf (1960) states that a major cause of the increase in bottom water temperatures as one travels into the northern Greenland Sea is the penetration of the warmer bottom water formed in the Norwegian Gyre (see Section IV). According to him, this water appears to travel north under the West Spitsbergen Current and eventually takes a position around the colder Arctic Bottom Water formed in the Greenland Gyre. He suggests that the volume of bottom water formed in the Norwegian Gyre is greater than that formed in the Greenland Gyre and that the colder water formed in the Greenland Gyre gradually loses its characteristics through mixing with warmer water from the Norwegian Gyre. Although this hypothesis is not unreasonable, it would seem that mixing of the bottom water formed in the Greenland Gyre with other warmer waters found in the region could also produce the observed temperature distribution. For example, if one examines the temperature and salinity distributions at 500 meters (Figs. 21 and 22), it becomes clear that in many cases water with temperatures warmer than 0°C and salinities almost the same as those in the Arctic Bottom Water was present. Moreover, there is evidence that the coldest Greenland Gyre Arctic Bottom Water has salinities which are slightly lower (≈ 34.88 ‰ instead of ≈ 34.91 ‰) than Arctic Bottom Water with slightly higher temperatures (Helland-Hansen and Nansen 1912, Gladfelter 1964). Thus, even if one took a rather extreme case and mixed Greenland Sea Gyre Arctic Bottom Water with a temperature of -1.15°C and a salinity of 34.88 ‰ with Atlantic Water of 35.05 ‰ and 4°C in proportions of 9 to 1, the resulting water would have a temperature of -0.63°C and a salinity of 34.90 ‰ . These characteristics fall well within the definition given for Arctic Bottom Water, but the mixture is now so warm that it could be mistaken for Arctic Bottom Water from the Norwegian Gyre. Therefore, it would appear that more study is necessary before the manner in which the coldest Arctic Bottom Water becomes warmer can clearly be defined, and before one definitely can assert in which of the two great gyres, the Norwegian or the Greenland, does the bulk of the Arctic Bottom Water originate. Certainly, mixing with waters other than bottom water from the Norwegian Gyre cannot be neglected when considering the processes which raise the temperatures of the colder bottom waters from the Greenland Gyre.

During the time of bottom water formation within the Greenland Gyre, it should be borne in mind that it is quite possible for waters with different temperatures to be formed (Helland-Hansen and Nansen 1912). Naturally, mixing of these waters as they travel from their source region could cause a rise in the minimum bottom water temperatures encountered.

4. Oxygen and Micronutrient Distributions.

High oxygen saturation values were found at all depths throughout the EDISTO survey region (Figs. 7, 10, and 11). This agrees with the findings of others (Lationov, et al. 1960, Nansen 1915, Sverdrup 1933) and with the dynamics of the region.

Since Arctic Bottom Water is formed at the surface in the same general area, and since there is some evidence that its replenishment is fairly rapid (Mosby 1959), it is not surprising that dissolved oxygen concentrations in the deeper layers were fairly high. Moreover, because the bottom waters are formed during the cold months when respiration exceeds photosynthesis, it is possible that a large portion of any organic matter which may have been present originally is oxidized before the waters contributing to the Arctic Bottom Water leave the surface. It is not likely that the amount of organic matter which sinks into the bottom water formation and is capable of being oxidized is very great either. If it was, one would expect to find significantly higher reactive phosphorus and nitrate concentrations in the deepest layers as they travel away from their source region, but this does not appear to be the case.

Photosynthetic processes must have been adding oxygen to the upper layers during the EDISTO survey and may have been partly responsible for the slight oxygen supersaturations sometimes encountered. Data presented by Richards (1957) indicate that it is unlikely that photosynthesis could exceed respiration at depths greater than 50 meters in the EDISTO survey region. Since the waters in the area were well stratified[5] during the EDISTO survey, one might not expect any net addition of oxygen by photosynthesis or by direct exchange with the atmosphere to have extended much deeper than 50 meters. Consequently, it is not surprising that oxygen saturations of 100% or greater were generally found only in the upper 50 meters of the water column (Figs. 7, 10, and 11).

Even though they were less than 100%, dissolved oxygen saturation values in the intermediate waters were still high indicating that at least some of these waters may have been closer to the surface in the not too distant past.

[5] The σ_t and depth values indicate that $10^5 \Delta\sigma_t / \Delta Z$ in the upper 50 meters were often greater than 1000 throughout the area, and extremely high stabilities were common in the surface layers in the western portions of the survey region.

As discussed above (Section IV), the Arctic Ocean's major inflow passes through the EDISTO survey region, and the deep waters of the Polar Basin appear to be supplied by a northward flow of Arctic Bottom Water. These inflows consist primarily of waters which originated in the Atlantic.[6] Estimates vary, but data presented by Coachman (1962) indicate that a reasonable estimate for the proportion of water originating in the Atlantic in the waters of the Arctic Ocean would be 70 to 80%. Thus, even in the waters of the East Greenland Current the proportion of water from the Atlantic Ocean should be high, and the Arctic Bottom Water and the waters of the West Spitsbergen Current should contain an even greater proportion of water from the Atlantic than the 70 to 80% given for the Arctic Ocean. In view of the above, it is not surprising that micronutrient concentrations in the survey area (Figs. 7, 9, 10, and 11) were fairly low because, as is well known, micronutrient concentrations in the North Atlantic also are low. Data gathered in the Norwegian Sea during a 1963 EDISTO survey[7] confirm the view that the inflowing Atlantic Water has low micronutrient concentrations. Here, in waters with salinities high enough to indicate that they were part of the Atlantic inflow ($\approx$35.2‰), the highest reactive phosphorus concentrations were approximately 1 µg-at/liter, the highest nitrate values were about 14 µg-at/liter, and the highest reactive silicate values were about 7 µg-at/liter. It is true that the higher nitrate and reactive phosphorus concentrations in the Arctic Bottom Water were slightly greater than those just mentioned and that maximum reactive silicate concentrations were considerably greater. This is to be expected, however, and does not necessarily indicate the presence of large quantities of waters not originating in the Atlantic. For example, it is quite possible that some of the micronutrients in the Atlantic Water discussed above had not yet been regenerated since all of the samples mentioned here were collected during the warmer months. The differences in maximum nitrate and reactive phosphorus concentrations were slight, and it is not surprising that large maximum reactive silicate differences were encountered. This could be due to the following factors: a) Regeneration of reactive silicate may proceed at a slower rate than that of nitrate and reactive phosphorus; b) Re-solution of silica from the bottom (Richards 1958); and c) Diatom frustules sinking faster than organic material.

As Figures 7, 9, 10, and 11 indicate, micronutrient concentrations generally increased with depth, and concentrations in the more shallow layers were often quite low. This, of course, is to be expected since photosynthetic processes were almost certainly lowering micronutrient concentrations in the near surface strata during the survey. Pronounced micronutrient maxima and a significant oxygen minimum were not present

---

[6] Although Arctic Bottom Water originates in the Greenland and Norwegian Seas, a consideration of the mass transports and current systems already described indicates that this water mass is formed mainly from waters originating in the Atlantic.

[7] National Oceanographic Data Center cruise No. 31167.

within a predictable depth interval as they often are in other regions. The absence of such features helps to confirm the view that most of the waters which have not been defined in this report can be considered to be mixtures of the three primary water masses defined in Section IV.

Figures 36 and 37 indicate that there were significant differences in micronutrient relationships in the three primary water masses. For a given reactive phosphorus concentration, reactive silicate concentrations in the Arctic Bottom Water were usually considerably higher than in Atlantic Water or Polar Water. This helps substantiate the view that processes such as the ones mentioned above lead to silicate enrichment of the deeper layers. In the three primary water masses, the lowest micronutrient concentrations generally were found in the Polar Water. This is not surprising, because, of the three, Polar Water was generally found closest to the surface, and its micronutrient levels probably had been reduced by phytoplankton activity. There was a tendency for nitrate concentrations corresponding to a given reactive phosphorus concentration to be much higher in Arctic Bottom Water and Atlantic Water than in Polar Water. Even when nitrate could not be detected, reactive phosphorus concentrations in the Polar Water were fairly high (≈ 0.6 µg-at/liter). Waters with high reactive phosphorus/nitrate ratios have been found in the East Siberian Sea and in Bering Strait, and undetectable concentrations of nitrate coupled with reactive phosphorus concentrations of as much as 1.5 µg-at/liter have been encountered in East Siberian Sea surface waters (Codispoti 1965). It is possible that the presence of appreciable quantities of such waters could be responsible for the similar phenomena noted in the Polar Water. However, other reasonable mechanisms could be invoked to explain this condition, and more study is necessary before its exact causes can be determined.

Figure 38 portrays a number of interesting features of the micronutrient relationships in the upper 50 meters of the survey region. Reactive silicate and reactive phosphorus appeared to be present in sufficient quantities to allow continued phytoplankton growth. Nitrate, on the other hand, was often present in such low concentrations that, in some localities, phytoplankton growth may have been limited by the supply of biologically available nitrogen. Some of the reactive phosphorus concentrations may appear to be low, but it must be remembered that the average ratio in which phytoplankton utilize silicon, nitrogen, and phosphorus appears to be approximately 22Si:16N:1P (Redfield, Ketchum, and Richards 1963). At some stations, nitrate concentrations in the surface layers appeared to be high enough to support continued phytoplankton growth, indicating that in these areas other factors were effective in limiting primary production. Differences in micronutrient relationships between the cold surface waters ($< -1°C$) which contain large portions of Polar Water and the warmer surface waters which contain large amounts of Atlantic Water are evident. Reactive phosphorus and reactive silicate values were often high in the colder surface waters, and nitrate concentrations were often quite low. The discussion of the high reactive phosphorus/nitrate ratios of the Polar Water

can also be applied to the colder surface waters and need not be repeated. Two possible explanations of the relatively high reactive silicate concentrations found in the colder surface waters are that they reflect the influence of waters from the Pacific and the influence of the large rivers which empty into the Arctic Ocean. High reactive silicate concentrations have been found in the waters of the Laptev Sea which are influenced by the Lena River's outflow and in Arctic Ocean waters which appear to enter through Bering Strait (Codispoti 1965). It must be emphasized that these explanations are very preliminary and other processes could also be quite important.

VII. SUMMARY

The results of this analysis of the oceanographic data collected during the 1964 EDISTO survey include the following:

a. Many of the prevailing ideas concerning the gross features of the oceanography of the region are shown to be correct.

b. At the time of this survey, the center of the East Greenland Current appeared to be farther east than is indicated on some earlier charts.

c. The meanders and gyres indicated by Figures 26 through 35 differ somewhat from those shown in some of the earlier current schemes.

d. Minimum bottom water temperatures in the survey region appeared to be warmer than they were at the beginning of the century.

e. More study appears to be necessary before one can say whether the bulk of the Arctic Bottom Water forms in the Norwegian Gyre or in the Greenland Gyre, or how the temperature of the Arctic Bottom Water formed in the Greenland Gyre is raised. There appear to be reasonable alternatives to Metcalf's (1960) views on these subjects.

f. High dissolved oxygen saturations found at great depths in the survey region can be explained by the proximity of areas of bottom water formation, by the oxidation of a large portion of organic material before the deeper waters leave the surface, and by the absence of a significant amount of sinking organic material.

g. In general, micronutrient concentrations in the survey region were low, indicating that water from the North Atlantic is the primary component of all of the waters in the northern Greenland Sea.

h. Photosynthetic processes appeared to be lowering the near surface micronutrient concentrations and, in some instances, raising oxygen concentrations.

i. In those cases where primary production may have been limited by a micronutrient deficiency, nitrate appears to have been the limiting nutrient.

j. No pronounced oxygen minimum or micronutrient maxima were encountered within a definite depth range in the survey area.

k. Micronutrient relationships differ for the three water masses. This can be explained to some extent by considering current theories on the formation and movement of these waters.

VIII. REFERENCES

Alekseev, A.P. and B.V. Istoshin, 1956. Chart of Constant Currents in the Norwegian and Greenland Seas. Trudy Pinro, No. 9, p 62-92.

________, 1960. Some Results of Oceanographic Research in the Norwegian and Greenland Seas. In Soviet Fisheries Investigations in Northern European Seas. Moscow, p 23-36, (Translation).

Air Weather Service, 1946. Climatology of the Arctic Regions. 314 pp.

Carpenter, J.H., 1966. New Measurements of Oxygen Solubility in Pure and Natural Waters. Limnol. and Oceanog., vol 2, p 264-277.

Chaplygin, E.I., 1959. The Waters of the East Greenland Current. Problemy Arktiki, No. 6, p 35-40.

Coachman, L.K., 1962. On the Water Masses of the Arctic Ocean. Ph.D. Thesis, Univ. Wash., Dept. of Ocean., 94 pp.

Codispoti, L.A., 1965. Physical and Chemical Features of the Waters in the East Siberian and Laptev Seas in the Summer. M.S. Thesis, Univ. Wash., Dept. of Ocean., 51 pp.

Defant, A., 1961. Physical Oceanography. Pergamon Press, London, vol I, 729 pp.

Det Danske Meteorlogiske Institut, 1961. Summaries of Weather Observations at Weather Stations in Greenland, 1954-1958. Charlottenlund, Denmark, 248 pp.

Duc D'Orleans, 1907. Croisiére Océanographique Accomplie a Bord de la BELGICA dans la Mer du Grönland. Brussels, Charles Bulens, 567 pp.

Gladfelter, W.H., 1964. Oceanography of the Greenland Sea, USS ATKA (AGB 3) Survey, Summer 1962. U.S. Naval Oceanographic Office, IMR No. 0-64-63, 154 pp.. (Unpublished manuscript).

Helland-Hansen, B. and F. Nansen, 1909. The Norwegian Sea, Its Physical Oceanography Based Upon the Norwegian Researches 1900-1904. In Norwegian Fishery and Marine Investigations. Bergen, Norway, vol II, 360 pp.

________, 1912. The Sea West of Spitsbergen, Christiania, Jacob Dybwad, 89 pp.

Jakhelln, A., 1936. Oceanographic Investigations in East Greenland Waters in the Summers of 1930-1932. Norges Svalbard-og Ishavsundersøkelser, Skrifter, No. 67.

Johnson, G.L. and O.B. Eckhoff, 1966. Bathymetry of the North Greenland Sea. Deep Sea Research, vol 13, p 1161-1173.

Kiilerich, A., 1945. On the Hydrography of the Greenland Sea. Meddeleser Om Grønland Bd, 144 Nr. 2 p 1-63.

Kislyakov, A.G., 1960. Fluctuation in the Regime of the Spitsbergen Current. In North European Seas, Moscow, p 39-49. (Translation).

Lationov, A.F., V.A. Shamontev, and A.V. Yanes, 1960. An Oceanographic Sketch of the Northern Part of the Greenland Sea. In Soviet Fisheries Investigations in North European Seas, Moscow, p 51-65. (Translation).

Metcalf, W.G., 1955. On the Formation of Bottom Waters in the Norwegian Basin, Trans. Amer. Geophys. Union, vol 36, p 596-600.

________, 1960. A Note on Water Movement in the Greenland-Norwegian Sea. Deep Sea Research, vol 7, p 190-200.

Mosby, H., 1959. Deep Water in the Norwegian Sea. Geofysiske Publikasjoner Geophysica Norvegica XXI, Nr. 3, p 1-62.

________, 1962. Water, Salt and Heat Balance of the North Polar Sea and of the Norwegian Sea. Geofysiske Publikasjoner Geophysica Norvegica XXIV, p 289-313.

Mullin, J.B. and J.P. Riley, 1955. The Spectrophotometric Determination of Nitrate With Particular Reference to Sea Water. Anal. Chim. Acta., vol 12, p 464-480.

Murphy, J. and J.P. Riley, 1962. A Modified Single Solution Method for the Determination of Phosphate in Natural Waters. Anal Chim. Acta., vol 27, p 31-66.

Nansen, F., 1902. The Oceanography of the North Polar Basin. In The Norwegian North Polar Expedition 1893-1896, Scientific Results, vol III.

________, 1915. Spitsbergen Waters, Oceanographic Observations During the Cruise of the VESLEMÖY to Spitsbergen in 1912, Christiania, Jacob Dybwad, 132 pp.

Rakestraw, N.W. and V.M. Emmel, 1938. The Solubility of Nitrogen and Argon in Sea Water. Jour. Phys. Chem., vol 42, p 1211-1215.

Redfield, A.C., and B.H. Ketchum, and F.A. Richards, 1963. The Influence of Organisms on the Composition of Sea Water. In The Sea, vol II, New York, John Wiley and Sons, p 26-77.

Richards, F.A., 1957. Oxygen in the Ocean. In Treatise on Marine Ecology and Paleoecology, Geol. Soc. Amer. Memoir 67, vol I, Wash., D.C., Nat. Acad. Sci., p 185-238.

________, 1958. Dissolved Silicate and Related Properties of Some Western North Atlantic and Caribbean Waters. J. Mar Res., vol 17, p 449-465.

Stafánsson, U., 1962. North Icelandic Waters. The University Res. Ins., Dept. of Fisheries, Reykjavík, 269 pp.

Strickland, J.D.H. and T.R. Parsons, 1960. A Manual of Sea Water Analysis. Bull. Fisheries Res. Board of Can. No. 125, 185 pp.

Sverdrup. H.U., 1933. Narrative and Oceanography of the NAUTILUS Expedition, 1931. Papers in Physical Oceanography and Meteorology, vol II Published by M.I.T. and W.H.O.I., 63 pp.

________, M.W. Johnson, and R.H. Fleming, 1942. The Oceans, New York, Prentice Hall, 1087 pp.

Swinnerton, J.W. and J.P. Sullivan, 1962. Shipboard Determination of Dissolved Gases in Sea Water by Gas Chromatography. NRL Rep. No. 5806, 13 pp.

Timofeev, V., 1958. An Approximate Determination of the Heat Balance of Arctic Basin Waters. Problemy Arktiki, vol 4, p 23-28.

U.S. Navy Hydrographic Office, 1955. Instruction Manual for Oceanographic Observations. H.O. Pub. No. 607, 208 pp.

________, 1958. Oceanographic Atlas of the Polar Seas, Part II Arctic. H.O. Pub. No. 705, 149 pp.

Zaitsev, G.N., M.V. Fedosov, N.L. Iljina, and I.A. Ermachenko, 1961. Components of the Water, Thermic, and Chemical Budget of the Greenland and Norwegian Seas. In Int. Council for the Exp. of the Sea, Contribution to Special I.G.Y. Meeting, 1959, p 46-52.

APPENDIX

Navigator's Estimate of the Quality of the Positions Given for the Oceanographic Stations

station number	navigational method	evaluation	station number	navigational method	evaluation
1	radar	excellent	26	radar	good
2	D.R.	fair	27	loran	good
3	celestial	good	28	loran	excellent
4	loran	excellent	29	D.R.	fair
5	loran	excellent	30	radar	excellent
6	loran/D.R.	good	31	loran	good
7	D.R.	poor	32	D.R.	poor
8	D.R./loran	fair	33	D.R.	fair
9	loran	excellent	34	loran	good
10	D.R.	poor	35	loran	good
11	D.R.	poor	36	D.R.	fair
12	D.R	fair	37	radar	excellent
13	D.R.	poor	38	radar	excellent
14	loran/D.R.	fair	39	radar	good
15	D.R.	fair	40	radar/D.R.	good
16	D.R.	poor	41	D.R.	good
17	loran	fair	42	loran	good
18	radar	good	43	loran	good
19	D.R.	fair	44	D.R.	fair
20	D.R.	fair	45	loran	good
21	loran	excellent	46	loran/D.R.	good
22	loran/D.R.	good	47	loran/D.R.	fair
23	loran	excellent	48	loran	excellent
24	loran	excellent	49	radar	excellent
25	D.R.	fair	50	radar	excellent

U.S. Naval Oceanographic Office
SOME RESULTS OF AN OCEANOGRAPHIC SURVEY IN THE GREENLAND SEA, SUMMER 1964, 49 p., including 38 figs., 2 tables.
(TR-202)

This report deals with some summer oceanographic features of the northern Greenland Sea. Emphasis is placed on the distributions of temperature, salinity, dissolved oxygen saturation, and micronutrients. A brief discussion of the current schemes of the area using dynamic calculations is presented.

An appendix presents the navigator's estimate of the positions given for the oceanographic stations.

1. Oceanography
2. Greenland Sea
3. USCGC EDISTO (W-AGB 284)

i. Title: Some Results of an Oceanographic Survey in the Greenland Sea, Summer 1964

ii. Author: Louis A. Codispoti

iii. TR-202

U.S. Naval Oceanographic Office
SOME RESULTS OF AN OCEANOGRAPHIC SURVEY IN THE GREENLAND SEA, SUMMER 1964, 49 p., including 38 figs., 2 tables.
(TR-202)

This report deals with some summer oceanographic features of the northern Greenland Sea. Emphasis is placed on the distributions of temperature, salinity, dissolved oxygen saturation, and micronutrients. A brief discussion of the current schemes of the area using dynamic calculations is presented.

An appendix presents the navigator's estimate of the positions given for the oceanographic stations.

1. Oceanography
2. Greenland Sea
3. USCGC EDISTO (W-AGB 284)

i. Title: Some Results of an Oceanographic Survey in the Greenland Sea, Summer 1964

ii. Author: Louis A. Codispoti

iii. TR-202

U.S. Naval Oceanographic Office
SOME RESULTS OF AN OCEANOGRAPHIC SURVEY IN THE GREENLAND SEA, SUMMER 1964, 49 p., including 38 figs., 2 tables.
(TR-202)

This report deals with some summer oceanographic features of the northern Greenland Sea. Emphasis is placed on the distributions of temperature, salinity, dissolved oxygen saturation, and micronutrients. A brief discussion of the current schemes of the area using dynamic calculations is presented.

An appendix presents the navigator's estimate of the positions given for the oceanographic stations.

1. Oceanography
2. Greenland Sea
3. USCGC EDISTO (W-AGB 284)

i. Title: Some Results of an Oceanographic Survey in the Greenland Sea, Summer 1964

ii. Author: Louis A. Codispoti

iii. TR-202

U.S. Naval Oceanographic Office
SOME RESULTS OF AN OCEANOGRAPHIC SURVEY IN THE GREENLAND SEA, SUMMER 1964, 49 p., including 38 figs., 2 tables.
(TR-202)

This report deals with some summer oceanographic features of the northern Greenland Sea. Emphasis is placed on the distributions of temperature, salinity, dissolved oxygen saturation, and micronutrients. A brief discussion of the current schemes of the area using dynamic calculations is presented.

An appendix presents the navigator's estimate of the positions given for the oceanographic stations.

1. Oceanography
2. Greenland Sea
3. USCGC EDISTO (W-AGB 284)

i. Title: Some Results of an Oceanographic Survey in the Greenland Sea, Summer 1964

ii. Author: Louis A. Codispoti

iii. TR-202

U.S. Naval Oceanographic Office
SOME RESULTS OF AN OCEANOGRAPHIC SURVEY IN THE GREENLAND SEA, SUMMER 1964, 49 p., including 38 figs., 2 tables.
(TR-202)

This report deals with some summer oceanographic features of the northern Greenland Sea. Emphasis is placed on the distributions of temperature, salinity, dissolved oxygen saturation, and micronutrients. A brief discussion of the current schemes of the area using dynamic calculations is presented.

An appendix presents the navigator's estimate of the positions given for the oceanographic stations.

1. Oceanography
2. Greenland Sea
3. USCGC EDISTO (W-AGB 284)

i. Title: Some Results of an Oceanographic Survey in the Greenland Sea, Summer 1964

ii. Author: Louis A. Codispoti

iii. TR-202

U.S. Naval Oceanographic Office
SOME RESULTS OF AN OCEANOGRAPHIC SURVEY IN THE GREENLAND SEA, SUMMER 1964, 49 p., including 38 figs., 2 tables.
(TR-202)

This report deals with some summer oceanographic features of the northern Greenland Sea. Emphasis is placed on the distributions of temperature, salinity, dissolved oxygen saturation, and micronutrients. A brief discussion of the current schemes of the area using dynamic calculations is presented.

An appendix presents the navigator's estimate of the positions given for the oceanographic stations.

1. Oceanography
2. Greenland Sea
3. USCGC EDISTO (W-AGB 284)

i. Title: Some Results of an Oceanographic Survey in the Greenland Sea, Summer 1964

ii. Author: Louis A. Codispoti

iii. TR-202

U.S. Naval Oceanographic Office
SOME RESULTS OF AN OCEANOGRAPHIC SURVEY IN THE GREENLAND SEA, SUMMER 1964, 49 p., including 38 figs., 2 tables.
(TR-202)

This report deals with some summer oceanographic features of the northern Greenland Sea. Emphasis is placed on the distributions of temperature, salinity, dissolved oxygen saturation, and micronutrients. A brief discussion of the current schemes of the area using dynamic calculations is presented.

An appendix presents the navigator's estimate of the positions given for the oceanographic stations.

1. Oceanography
2. Greenland Sea
3. USCGC EDISTO (W-AGB 284)

i. Title: Some Results of an Oceanographic Survey in the Greenland Sea, Summer 1964

ii. Author: Louis A. Codispoti

iii. TR-202

U.S. Naval Oceanographic Office
SOME RESULTS OF AN OCEANOGRAPHIC SURVEY IN THE GREENLAND SEA, SUMMER 1964, 49 p., including 38 figs., 2 tables.
(TR-202)

This report deals with some summer oceanographic features of the northern Greenland Sea. Emphasis is placed on the distributions of temperature, salinity, dissolved oxygen saturation, and micronutrients. A brief discussion of the current schemes of the area using dynamic calculations is presented.

An appendix presents the navigator's estimate of the positions given for the oceanographic stations.

1. Oceanography
2. Greenland Sea
3. USCGC EDISTO (W-AGB 284)

i. Title: Some Results of an Oceanographic Survey in the Greenland Sea, Summer 1964

ii. Author: Louis A. Codispoti

iii. TR-202

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* U.S. NAVAL OCEANOGRAPHIC OFFICE	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED
	2b. GROUP

3. REPORT TITLE

SOME RESULTS OF AN OCEANOGRAPHIC SURVEY IN THE NORTHERN GREENLAND SEA, SUMMER 1964

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Technical Report August-September 1964

5. AUTHOR(S) *(First name, middle initial, last name)*

LOUIS A. CODISPOTI

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1968	45	39

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. 202-02	TR-202
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

U.S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users mail request through: Commander, U.S. Naval Oceanographic Office, Washington, D.C. 20390 ATTN: Code 40

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U.S. Naval Oceanographic Office

13. ABSTRACT

Oceanographic data were collected during a cruise of USS EDISTO (AGB 2) to the northern Greenland Sea and adjacent Arctic Ocean during the summer of 1964. The resulting data indicate that many of the prevailing ideas concerning the oceanography of the region are correct, but some modifications and additions are suggested.

The center of the East Greenland Current appeared to be farther east than is indicated on some earlier charts, and the meanders and gyres also differed from those shown in some earlier current schemes.

Minimum bottom water temperatures in the survey region appear to be warmer than they were at the beginning of the century, and some current ideas on the formation and movement of Arctic Bottom Water do not seem to be well substantiated.

High dissolved oxygen saturations were found at great depths and can be explained by the proximity of areas of bottom water formation, by the oxidation of a large portion of organic material before the deeper waters left the surface, and by the absence of a significant amount of sinking organic material.

Micronutrient concentrations were low indicating that water from the North Atlantic was the primary component of the waters in the survey region. Photosynthetic processes appeared to be lowering near-surface micronutrient concentrations and, in some instances, raising oxygen concentrations. In cases where production may have been limited by micronutrient deficiencies, nitrate appears to have been the limiting nutrient. No pronounced oxygen minimum or micronutrient maxima were encountered within a definite depth range in the survey area. Micronutrient relationships in the different water masses differed and can be explained to some extent by current theories on the formation and movement of these waters.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
OCEANOGRAPHY ARCTIC OCEANOGRAPHY GREENLAND SEA USCGC EDISTO (W-AGB 284)						